

8-86...

DOE/NASA/0032-27  
NASA CR-175045  
MTI 86ASE507SA9

12-0  
8-11

# **AUTOMOTIVE STIRLING ENGINE DEVELOPMENT PROGRAM**

**SEMIANNUAL TECHNICAL PROGRESS REPORT  
FOR PERIOD: JULY 1 - DECEMBER 1985**

(NASA-CR-175045) AUTOMOTIVE STIRLING ENGINE DEVELOPMENT PROGRAM Semiannual Progress Report, 1 Jul. - 31 Dec. 1985 (Mechanical Technology, Inc.) 66 p	CSCI 13F G3/85	N86-30579 Unclas 43500
---	-------------------	------------------------------

**Mechanical Technology Incorporated**

**May 1986**

**Prepared for  
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION  
Lewis Research Center  
Under Contract DEN 3-32**

**for  
U.S. DEPARTMENT OF ENERGY  
Conservation and Renewable Energy  
Office of Vehicle and Engine R&D**

### **NOTICE**

This report was prepared to document work sponsored by the United States Government. Neither the United States nor its agent, the United States Department of Energy, nor any Federal employees, nor any of their contractors, subcontractors or their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product or process disclosed, or represents that its use would infringe privately owned rights.

**AUTOMOTIVE STIRLING ENGINE DEVELOPMENT PROGRAM**

**MTI 86ASE507SA9**

**SEMIANNUAL TECHNICAL PROGRESS NARRATIVE REPORT**

**FOR PERIOD OF JULY 1 - DECEMBER 31, 1985**

**May 1986**

**Approved By:**

  
**William D. Ernst**  
**ASE Program Manager**

**Approved/Ratified  
by NASA:**

  
**William K. Tabata**

**MECHANICAL TECHNOLOGY INCORPORATED**  
**968 Albany-Shaker Road**  
**Latham, New York 12110**

## TABLE OF CONTENTS

<u>Section</u>	<u>Page</u>
INTRODUCTION.....	viii
I SUMMARY.....	1-1
Overall Program Objectives.....	1-1
Major Task Descriptions.....	1-1
Program Schedule.....	1-3
Program Overview, Status and Plans.....	1-3
RESD.....	1-3
Component and Technology Development.....	1-3
Heater Head Development.....	1-5
Materials Development.....	1-5
Seals Development.....	1-5
Controls and Auxiliaries Development.....	1-6
Mod I Engine Test Program.....	1-7
Mod II Engine.....	1-7
Mod II Design.....	1-7
Mod II Analysis.....	1-8
Mod II Hardware.....	1-8
II REFERENCE ENGINE SYSTEM DESIGN.....	2-1
III COMPONENT AND TECHNOLOGY DEVELOPMENT.....	3-1
External Heat System.....	3-1
Mod II Combustion System Performance.....	3-1
EHS Transient Analysis.....	3-2
CGR Combustor Durability.....	3-3
Mod II Fuel Nozzle/Igniter Development.....	3-3
Alternate Fuel/Conical Nozzle Development.....	3-4
Ceramic Preheater Development.....	3-5
Hot Engine System Development.....	3-6
Heater Head Heat Transfer.....	3-6
Materials and Process Development.....	3-6
Mod II Piston Base/Rod/Crosshead Fatigue Test.....	3-7
Heater Head Manifold Fatigue Test, Configuration No. 1.....	3-7
Proof-Fatigue Testing - Hydrogen Storage Cylinder.....	3-8
Cooler/Liner Heat Treat Optimization.....	3-8
Fatigue Strength Enhancement - XF-818.....	3-8
Cold Engine System (CES) Development.....	3-9
Main Seals.....	3-9
Piston Rings.....	3-10
Static Seals.....	3-10

PRECEDING PAGE BLANK NOT FILMED

## TABLE OF CONTENTS (Concluded)

<u>Section</u>		<u>Page</u>
	Controls System/Auxiliaries Development.....	3-10
	Combustion Control.....	3-10
	Control System Analysis.....	3-12
	DEC.....	3-12
	MPC.....	3-13
	MPC System Design.....	3-13
	Mod II Electronics Development.....	3-14
	Electronics Development for the Blower and Alternator.....	3-14
IV	MOD I ENGINE DEVELOPMENT.....	4-1
	Mod I Hardware Development.....	4-1
	Mod I Hardware Follow-Up Report.....	4-1
	Mod I High Temperature Heater Heads.....	4-1
	Crankcase Bedplate Cracking.....	4-1
	Heater Tube Failures.....	4-1
	Cylinder Liner Top O-Ring Deterioration.....	4-1
	Hydrogen Compressor Small End Bearing Bushings.....	4-1
	Mod I Engine Test Program.....	4-2
	Mod I Engine No. 3.....	4-2
	Upgraded Mod I Engine No. 5.....	4-2
	Upgraded Mod I Engine No. 6.....	4-3
	Mod I Engine No. 7.....	4-3
	Upgraded Mod I Engine No. 8.....	4-3
	Upgraded Mod I Engine No. 9.....	4-3
	Mod I/Upgraded Mod I Analysis.....	4-4
V	MOD II PRELIMINARY DESIGN.....	5-1
	Introduction.....	5-1
	PCV.....	5-1
	Hydrogen Compressor.....	5-2
	Mod II Analysis.....	5-4
	Mod II Hardware Procurement.....	5-6
VI	TECHNICAL ASSISTANCE.....	6-1
	Lateral Rod Motion.....	6-1
VII	PRODUCT ASSURANCE.....	7-1
	Quality Assurance Overview.....	7-1
	Mod I QAR Experience.....	7-1

# LIST OF FIGURES

Section		Page
1-1	Mod II Engine Development Program Schedule.....	1-4
2-1	100 kW RESD Net Power.....	2-2
2-2	100 kW RESD Net Power.....	2-2
2-3	100 kW RESD Cross-Sectional Layout.....	2-2
3-1	Effect of Heater Head Blockage on Engine No. 3 NO <sub>x</sub> Emissions with Air Atomization at 720°C.....	3-16
3-2	Effect of Atomizing Air on Measured Performance Rig %CGR with the BOM Nozzle.....	3-16
3-3	Effect of Atomizing Airflow on NO <sub>x</sub> Emissions.....	3-16
3-4	Effect of Atomizing Fluid on Engine No. 3 NO <sub>x</sub> Emissions at Different Heater Head Set Temperatures.....	3-16
3-5	Effect of Heater Head Blockage on Engine No. 3 NO <sub>x</sub> Emissions with Exhaust Gas Atomization at 720°C.....	3-17
3-6	Effect of Mod II Heater Head ΔP on NO <sub>x</sub> Emissions.....	3-17
3-7	Effect of Exhaust Gas Atomization on NO <sub>x</sub> Emissions.....	3-17
3-8	Effect of Reduced BOM Nozzle Atomizing Airflow on Engine No. 3 Soot Emissions at 720°C.....	3-17
3-9	Soot versus Particulates with the CGR Combustor - Spirit Vehicle.....	3-18
3-10	Effect of Tube Temperature on Engine No. 5 NO <sub>x</sub> Emissions.....	3-18
3-11	Effect of Tube Temperature on Engine NO. 5 HC Emissions.....	3-18
3-12	Effect of Tube Temperature on Engine No. 5 CO Emissions.....	3-18
3-13	Effect of Tube Temperature on Engine No. 5 Smoke Number.....	3-19
3-14	Variation of CGR Combustor Shell Temperature Along the Mixing Tube Centerline.....	3-19
3-15	BOM Nozzle Thermocouple Locations.....	3-19
3-16	Effect of Atomizing Airflow on Nozzle Temperature.....	3-19
3-17	Effect of Fuel Flow on Nozzle Temperature.....	3-20
3-18	Effect of BOM Nozzle Leakage on Soot Emissions at 720°C.....	3-20
3-19	Modified BOM Nozzle with Concentric Center Electrode.....	3-20
3-20	Effect of BOM Igniter on CGR Ignition Delay.....	3-20
3-21	Standard Upgraded Mod I BOM Nozzle Cold Flow Calibration.....	3-20
3-22	Standard Upgraded Mod I BOM Nozzle Cold Flow Calibration.....	3-21
3-23	Increased Momentum Fuel Spin Chamber Conical Nozzle.....	3-21
3-24	CGR Combustor Modifications.....	3-21
3-25	Comparison of Soot Emissions with CGR Burning Gasoline.....	3-21
3-26	Effect of Fuel on Smoke Number.....	3-22
3-27	Effect of Fuel Nozzle and Atomizing Airflow on Diesel Fuel Soot Emission with a CGR Combustor.....	3-22
3-28	Ceramic Preheater Plate Cracks.....	3-22
3-29	Comparison of NTU, Nu, and H with Front Test Section - 0217 when Run with and without Rear Test Section, Least Squares Fit of Data (6/85-8/85).....	3-22
3-30	Comparison of NTU, Nu, and H with Front Test Section - 0301 when Run with and without Rear Test Section, Least Squares Fit of Data (6/85-8/85).....	3-22
3-31	Comparison of Rear Row Performance (218) for Various Front Row Geometries and Alone.....	3-23
3-32	Front Row Effect on Rear Row.....	3-23

## LIST OF FIGURES (Concluded)

<u>Section</u>	<u>Page</u>
3-33 Ntu versus Re - 218 Run Together with 301 and without 20 mm Spacer.....	3-23
3-34 CVS Endurance Cycle for Engines No. 6 and 7.....	3-23
3-35 Compound Main Seal.....	3-24
3-36 Single-Solid Piston Ring.....	3-24
3-37 Piston Ring Performance, Engine No. 5.....	3-24
3-38 Controls, Auxiliaries, and Components Development in Engine Cell.....	3-24
3-39 Transient Tests on DAFC (1 data scan/sec).....	3-25
3-40 Urban $\lambda$ Response: K-Jetronic and DAFC.....	3-25
3-41 Temperature Control with and without Anticipation.....	3-25
3-42 Electric Actuator Performance - Up-Power Transient from Idle..	3-25
3-43 Electric Actuator Performance - Low Pressure (30 bar $P_{max}$ ) Low Speed (400 rpm) Idle.....	3-26
3-44a Typical Two-Tank System Pump-Down.....	3-26
3-44b Typical Two-Tank System Pump-Down (Cont'd).....	3-26
3-45 Two-Tank System Maximum Power Transient Test.....	3-26
4-1 Engine Operating Hours at USAB.....	4-5
4-2 Engine Operating Hours at MTI.....	4-5
4-3 Engine No. 9 System Efficiency Prepared for Genset Installation.....	4-5
4-4 Engine No. 9 BSFC as Prepared for Genset Installation.....	4-5
4-6 Engine No. 9 Baseline Performance.....	4-6
4-7 Engine No. 9 Performance with Gear Reducer.....	4-6
4-8 Engine No. 9 Genset Performance.....	4-6
5-1 Cross Section of Actuator.....	5-7
5-2 Schematic Representation of Mod II Hydrogen Compressor.....	5-7
5-3 Hydrogen Compressor Assembly for Mod II Engine.....	5-7
5-4 P-40R Cylinder Cross Section.....	5-7
7-1 Upgraded Mod I Engine Major Failures and Discrepancies.....	7-2
7-2 Drive Unit and Power-Control System Failiures and Discrepancies.....	7-2
7-3 Hot Engine, Cold ENgine, and EHS Failuires and Discrepancies..	7-3
7-4 Auxiliaries and Miscellaneous Items, Failiures and Discrepancies.....	7-4

## LIST OF TABLES

<u>Section</u>		<u>Page</u>
2-1	Line Haul Truck System Parameters.....	2-2
2-2	Simple Life Cycle Cost Model (Engine Related).....	2-2
3-1	Performance Impact of Mod II Changes on EHS Performance.....	3-1
3-2	Results of Complete CVS-Cycle Tests (Phase I, II, and III)....	3-2
3-3	Test Cycle - Mod II Piston Base/Rod/Crosshead.....	3-7
4-1	Final Generator Set Performance.....	4-4
5-1	IC-Celebrity.....	5-6
7-1	Major Problems Summary.....	7-2
7-2	Operating Times versus Failures as of December 30, 1985.....	7-1



## INTRODUCTION

In March 1978, a Stirling-engine development contract, sponsored by the Department of Energy (DOE) and administered by National Aeronautics and Space Administration (NASA)/Lewis Research Center, was awarded to Mechanical Technology Incorporated (MTI) for the purpose of developing an Automotive Stirling Engine (ASE) and transferring Stirling-engine technology to the United States. The program team consisted of MTI as prime contractor, contributing their program management, development, and technology-transfer expertise; United Stirling of Sweden (USAB) as major subcontractor for Stirling-engine development; and AM General (AMG) as major subcontractor for engine and vehicle integration.

Most Stirling-engine technology previously resided outside of the United States, and was directed at stationary and marine applications. The ASE Development Program was directed at the establishment and demonstration of a base of Stirling-engine technology for the automotive application by September 1984. The high-efficiency, multi-fuel capability, low-emissions, and low-noise potential of the Stirling engine made it a prime candidate for an alternative automotive-propulsion system.

ASE Program logic called for the design of a Reference Engine System Design (RES D) to serve as a focal point for all component, subsystem, and system development within the program. The RES D was defined as the best-engine design generated within the program at any given time. The RES D would incorporate all new technologies with reasonable expectations of development by the end of the program and which provide significant performance improvements relative to the risk and cost of their development. The RES D would also provide the highest fuel economy possible while still meeting

other program objectives.

A schedule was defined within the ASE Program to design two experimental engine versions of the RES D. The first-generation engine system, the Mod I, was designed early in the program, and has been on test since January 1981. The second-generation engine, designated the Mod II, was originally scheduled to be designed in 1981 to demonstrate the final program objectives. However, it was postponed to 1984 due to Government funding cutbacks.

Through the course of the program, the Mod I has been modified and upgraded wherever possible, to develop and demonstrate technologies incorporated in the RES D. As a result, the program followed a "proof-of-concept" development path whereby the Upgraded Mod I design emerged as an improved engine system, proving specific design concepts and technologies in the Mod II that were not included in the original Mod I design. This logic was recognized as having inherent limitations when it came to actual engine hardware, since Mod I hardware was larger and, in some cases, of a fundamentally different design than that of the Mod II.

Nevertheless, some of the new technology incorporated in the RES D has been successfully transferred to the Upgraded Mod I engine. Iron-based materials were used in place of costly cobalt-based materials in the Hot Engine System (HES) which was designed to operate at 820°C heater head temperature (the Mod I was tested at 720°C). Smaller, lighter designs were incorporated into the upgraded engine to optimize for better fuel economy and to reduce weight (the Upgraded Mod I engine was 100 lb lighter than the Mod I). The RES D has been revised periodically throughout the course of the program to incorporate new concepts and technologies aimed at improving engine efficiency

or reducing manufacturing cost. The RESD was last revised in May 1983. Emphasis of this most recent update of the RESD was to reduce weight and manufacturing cost of the ASE to within a close margin of that for the spark-ignition engine, while exceeding the fuel mileage of the spark-ignition engine by at least 30%.

The 1983 RESD configuration was changed substantially from previous designs to achieve these goals. The new design used a single-shaft V-drive, rather than the two-shaft U-drive system of the Mod I; an annular heater-head and regenerator rather than the previous cannister configuration; and a simplified control system and auxiliary components. By these measures, the projected manufacturing cost of the May 1983 RESD was reduced by more than 25% and total engine system weight was reduced by 47% in comparison to the Upgraded Mod I engine, while engine efficiency and power remained approximately the same. This updated RESD has a predicted combined mileage of 41.1 mpg using unleaded gasoline, which is 50% above the projected spark-ignition engine mileage for a 1984 X-body vehicle with a curb weight of 2870 lb.

Since the RESD update in May 1983, the Mod II design effort has been focused on translating the new RESD concepts into preliminary Mod II design drawings. Casting drawings of the annular heater head and single-piece V-block were implemented and reviewed with vendors; the lower end drive system was designed for a durability rig to test the life and operational behavior of the bearings, seal systems, and gas passages. An analysis was performed on the Mod II engine/vehicle system to select the vehicle and matching drive train components such as transmission, gear ratios, and axle ratio.

The preliminary design phase of the Mod II was concluded in September 1984 with a Technology Assessment which selected specific technologies and configurations from competing contenders for each component of the Mod II engine.

These component configurations were then moved into the initial detail design phase where the design was completed in preparation for manufacturing. Component development was intensified for certain components that needed further improvements; CGR combustor, as well as controls and auxiliaries. The Spirit vehicle with Upgraded Mod I engine No. 8, after the successful completion of its testing during the General Motors (GM) portion of the Industry Test and Evaluation Program (ITEP), was utilized to evaluate new controls and auxiliaries concepts to be incorporated in the Mod II. Analysis efforts were concentrated on finalizing loss models, and algorithms for all aspects of the Mod II engine which were then integrated into computer codes to be used in optimizing the engine.

In January 1985, the CGR combustor external heat system (EHS) was selected as the prime design and the first optimization of the Mod II was completed. This optimization identified key engine parameters such as power and efficiency levels, bore and stroke, as well as key component design specifications, such as preheater plate aspect ratios, regenerator and cooler dimensions, etc. This initial optimization was then honed and refined through many successfully smaller iterations, including a preliminary final version presented at the basic Stirling engine (BSE) Design Review, until the design was finalized at the Stirling engine system (SES) Design Review in August 1985. Improvements in the projected Mod II engine design and performance resulted from vendor feedback on the prototype Mod II V-block and heater heads, from component development tests of low idle fuel consumption and from extended Mod I engine testing of seals, piston rings and appendix gap geometry. During this period as well, a 1985 Celebrity with a 68.9 kW (92 hp) I4 engine was selected for the Mod II vehicle installation. This vehicle is representative of the vehicle class (3000-3500 lb front wheel drive) that is extremely popular in the U.S. automotive market. It also has

the best fuel economy in its class, thereby establishing a high level internal combustion (IC) reference mileage for the Mod II evaluation.

The BSE and SES designs were both completed on schedule, and the design was approved for manufacture by NASA. The final performance predictions indicate the Mod II engine design will meet or exceed the original program goals of 30% improvement in fuel economy over a conventional IC powered vehicle, while providing acceptable emissions. This was accomplished while simultaneously reducing Mod II engine weight to a level comparable with IC engine power density, and packaging the Mod II in a 1985 Celebrity with no external sheet metal changes. The projected mileage of the Mod II Celebrity for the combined urban and highway CVS cycle is 40.9 mpg which is a 32% improvement over the IC Celebrity. If additional potential improvements are verified and incorporated in the Mod II, the mileage could increase to 42.7 mpg.

During this report period the Mod II BSE engine procurement was completed for all but a few components and the SES procurement was initiated. Two modifications to the final engine design were incorporated in the procurement for the first build of the Mod II in order to assure that the engine start date of January 31, 1986 would be met. First, a machined steel block was designed with comparable inner passages but simplified outer surfaces as an analogue to the cast iron block. Second, the preliminary design of the cast annular heater head with two tube manifolds (known as configuration No. 1) was ordered. In addition a parallel procurement was initiated for the final build hardware which would use the cast-iron V-block and a single manifold heater head (known as configuration No. 3). These designs were selected for the Mod II be-

cause of lower weight and improved performance, respectively.

The assembly of the Mod II has been initiated on schedule using the modified components. Also during this report period a number of Mod II technologies were successfully tested on Mod I engine No. 5. Components evaluated included the digital air/fuel control (DAFC), electrically-driven blower system, electrically actuated power control valve (PCV), two-tank power control system, and the single-solid piston ring.

During 1985 the number of engine hours climbed dramatically to 14,239 which is an increase of 2827 hrs in the last six months. Engines No. 6 and 7 have been engaged in endurance tests of high temperature operation and seals/piston ring life, respectively.

As emphasis has shifted to Mod II engine development, the number of active Mod I engines in the program has been reduced. Engines No. 3 and 6 will continue in operation with engine No. 3 now being used for piston ring, seals and combustion development. Engine No. 7 will be converted to a motoring rig. Engine No. 8 will continue in operation to power the Spirit vehicle for Mod II SES development tests. Engine No. 5 will be dropped from the program in 1986 and will be dedicated to an Air Force Van power plant demonstration program at the Langley, Virginia, Air Force Base.

The ASE Program remains on schedule for the first testing of a Mod II engine in January 1986. During the next Semiannual period attention will be focused on assembly, start-up and development of Mod II BSE engines No. 1 and 2, completion of the procurement of the SES hardware and preparation for the start-up of the Mod II SES in June 1986.

## I. SUMMARY

Since the inception of the ASE Program in 1978, 13 Quarterly Technical Progress Reports were issued under NASA Contract No. DEN3-32, "ASE Development Program". However, reporting was changed to a Semiannual format in July 1981. This report, the ninth Semiannual Technical Progress Report issued under the contract, and covering the period of July 1 through December 31, 1985, includes technical progress only.

### Overall Program Objectives

The overall objective of the ASE Program is to develop an ASE system which, when installed in a late-model production vehicle, will:

- Demonstrate an improvement in combined metro/highway fuel economy of at least 30% over that of a comparable spark-ignition-engine powered production vehicle, based on EPA test procedures.\*
- Show the potential for emissions levels less than:  $\text{NO} \leq 0.4 \text{ g/mi}$ ,  $\text{HC} \leq 0.41 \text{ g/mi}$ ,  $\text{CO} \leq 3.4 \text{ g/mi}$ , and a total particulate level  $\leq 0.2 \text{ g/mi}$  after 50,000 miles.

In addition to the previous objectives, which are to be demonstrated quantitatively, the following system design objectives were also considered:

- Ability to use a broad range of liquid fuels from many sources, including coal and shale oil.
- Reliability and life comparable to current-market powertrains.

- A competitive initial cost and a life-cycle cost comparable to conventionally powered automotive vehicles.
- Acceleration suitable for safety and consumer considerations.
- Noise/safety characteristics that meet the currently legislated or projected Federal Standards.

### Major Task Descriptions

The major ASE Program tasks are described below:

Task 1 - Reference Engine - This task, intended to guide component, subsystem, and engine system development, involves the establishment and continual updating of an RESD, which will be the best engine design that can be generated at any given time, and that can provide the highest possible fuel economy while meeting or exceeding other final program objectives. The engine will be designed for the requirements of a projected reference vehicle that will be representative of the class of vehicles for which it might first be produced, and it will utilize all new technology (expected to be developed by 1987) that is judged to provide significant improvement relative to the risk and cost of its development.

Task 2 - Component/Technology Development - Guided by the RESD, this task will include conceptual and detailed design/analyses, hardware fabrication and assembly, and component/subsystem testing in laboratory test rigs. When an adequate performance level has been demonstrated, the component and/or sub-

\*Automotive Stirling and Spark-ignition engine systems will be installed in identical model vehicles that will give the same overall vehicle driveability and performance.

system design will be configured for in-engine testing and evaluated in an appropriate engine dynamometer/vehicle test installation.

The component development tasks, directed at advancing engine technology in terms of durability/reliability, performance, cost, and manufacturability, will include work in the areas of combustion, heat exchangers, materials, seals, engine drive train, controls, and auxiliaries.

Task 3 - Technology Familiarization - The USAB P-40 Stirling engine, which was available at the beginning of the program, was used as a baseline for familiarization; to evaluate current engine operating conditions and component characteristics; and as a test bed for component/subsystem performance improvement; and, to define problems associated with vehicle installation. Three P-40 engines were built and delivered to the U.S. team members - one was installed in a 1979 AMC Spirit. A fourth P-40 engine was built and installed in a 1977 Opel sedan for testing in Sweden. The baseline P-40 engines were tested in dynamometer test cells and automobiles. Test facilities were constructed at MTI to accommodate the engine test program and to demonstrate required technology transfer.

Another activity under Task 3 during 1984 was the Industry Test and Evaluation Program (ITEP). Major purposes of ITEP were to extend familiarity and interest in Stirling engine technology to industry, to provide an independent evaluation of ASE technology, to broaden the base of engine test experience, and to give automotive/engine manufacturers an opportunity to make recommendations for improvements in design and manufacturability. Two Mod I engines were procured, assembled, and tested for delivery to automotive/engine manufacturing companies for test and evaluation.

Task 4 - Mod I Engine - A first generation engine (the Mod I) was developed

using USAB P-40 and P-75 engine technology. The prime objective was to increase power density and overall engine performance.

The Mod I engine represented an early experimental version of the RESD, but was limited by the technology that could be confirmed in the time available. The Mod I was not intended to achieve any specific fuel economy improvements. Rather, it was meant to verify concepts incorporated in the RESD, and to serve as a stepping stone toward the Mod II, thus providing an early indication of the potential to meet the final ASE Program objectives.

Three Mod I engines were manufactured by USAB and tested in dynamometer test cells to establish their performance, durability, and reliability. Continued testing and development was necessary to meet preliminary design performance predictions. One additional Mod I engine was manufactured, assembled, and tested in the United States by MTI. A production vehicle was procured and modified to accept one of the engines for installation. Tests were conducted under various steady-state, transient, and environmental conditions to establish engine-related driveability, fuel economy, noise, emissions, and durability/reliability.

The Mod I engine was upgraded through design improvements to provide a "proof-of-concept" demonstration of selected advanced components defined for the RESD and Mod II.

Task 5 - Mod II Engine - The Mod II engine (the second-generation ASE design) is based on the 1983 RESD, the development experience of the Mod I engine system, and technologies and components developed under Task 2. The goal of the Mod II is to demonstrate the overall ASE Program objectives in an engine/vehicle system. Although postponed in 1981, this task was reinstated during the first half of 1984 as the preliminary design of the Mod II engine system was activated. In the latter half of 1984, this has transitioned

into a preliminary detail design of the Mod II. The final design was completed in the first half of 1985. Hardware procurement and start of assembly of the Mod II engine was accomplished in the later half of 1985.

#### Task 6 - Prototype Study - Postponed.

Task 7 - Computer Program Development - Analytical tools have been developed that are required to simulate and predict engine performance. This effort included the development of a computer program specifically tailored to predict SES steady-state cyclical performance over the complete range of engine operations. Using data from component, subsystem, and engine system test activities, the program will continuously improve and be verified throughout the course of the ASE Program.

Task 8 - Technical Assistance - Technical assistance will be provided to the Government as requested.

Task 9 - Program Management - Work under this task will provide total program control, administration, and management, including: reports, schedules, financial activities, test plans, meetings, reviews, and technology transfer. This task also provides for an extensive Quality Assurance Program.

#### **Program Schedule**

A current schedule of the major milestones and the Mod II Engine Development Program is presented in Figure 1-1. This schedule has been maintained since its inception in the fall of PY 1984 when the Mod II program was reactivated.

#### **Program Overview, Status and Plans**

During 1985, efforts on the ASE Program were focused on finalizing the design and accomplishing the procurement of BSE hardware for the initial Mod II engine. Assembly of the engine was initiated in November with a planned test start date of January 1986. Development of systems

for the Mod II engine was in process utilizing Upgraded Mod I engines both in the dynamometer cells and in the Spirit vehicle.

#### RESD

Activity in this task was initiated to investigate potential designs for higher power level Stirling engines. The objective of this investigation is to broaden the applicability of Stirling engines in the transportation sector, in heavier automobiles and in other vehicle installations. Line haul truck, city bus, and delivery van installations were considered. It was concluded that the bus/van application indicated good potential for the Stirling engine. Engine concepts were defined for a range of power output up to 300 kW.

#### Component and Technology Development

Component and technology development is directed toward advancing Stirling engine technology and/or components in terms of performance, cost, manufacturability, durability, and reliability as defined by their application in the RESD.

This development involves a sizeable effort, as it includes virtually all technological areas in the engine (e.g., combustors, heat exchangers, materials, seals, mechanical drive systems, controls, and auxiliaries).

Fuel Nozzle and Combustor Development - A concentrated effort was initiated to address a nozzle combustor configuration to achieve Mod II goals of low emissions and low idle fuel flow. Tests conducted indicated that the combination of reduced atomizing airflow (desired for improved EHS efficiency at low engine power) and the reduced recirculation of CGR caused by the expected Mod II heater head pressure drop would result in increased NO<sub>x</sub> emissions and soot in the low power range.

Continued fuel nozzle development has identified a promising nozzle concent

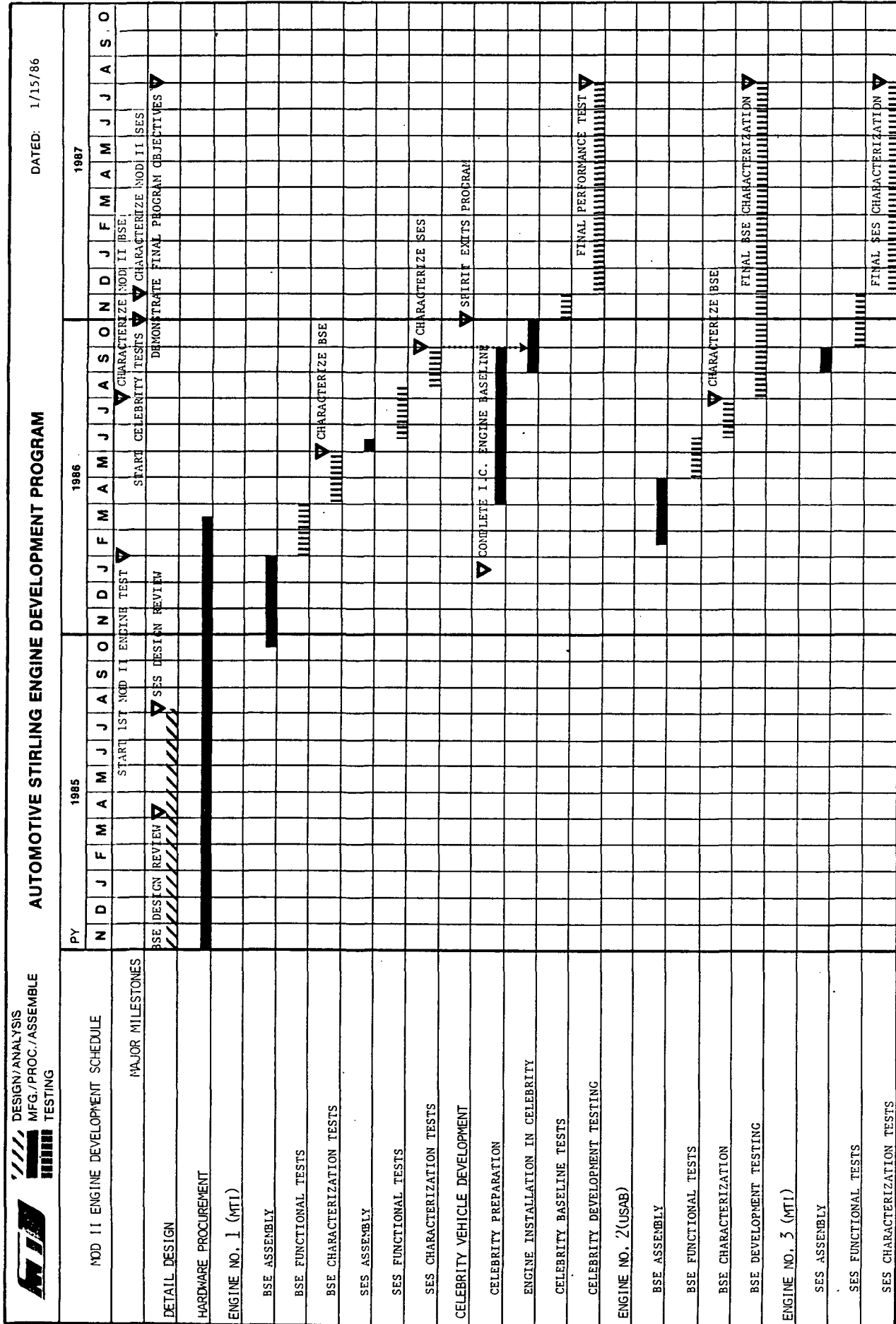


Fig. 1-1 Mod II Engine Development Program Schedule

which provides acceptable performance in a CGR combustor throughout the engine operating range on both gasoline and diesel fuels. The nozzle is a three-hole conical, derived from the original single-hole conical concept. The nozzle provides combustor temperature spread and emissions comparable to or better than the Bill of Materials (BOM) nozzle without exhibiting the plugging tendencies of the BOM nozzle.

Combustor durability improvement activity continued in this report period. Oxidation-resistant coating was applied to an EGR combustor and the combustor tested for 140 hrs to date without any sign of degradation. The program goal is to develop combustors to a life rating of 3500 hrs.

Transient testing was initiated to address optimization for vehicle operation. Start-up tests are underway to evaluate the impact of lambda, atomizing airflow, and fuel flow on emissions, fuel consumption, and drive-away time. These tests will continue in 1986. Driving cycle tests were conducted to evaluate the contribution of soot to particulate emissions. It was determined that there was no correlation between soot and particulate levels, indicating that soot is not a major particulate component. Start-up tests with a range of different tube temperature levels were conducted to evaluate temperature impact on driving cycle emissions. Relative to steady-state measurements, the low temperatures encountered during starts resulted in lower NO<sub>x</sub> and higher CO/HC emissions levels. These findings will be used to more accurately predict vehicle driving cycle emissions.

#### Heater Head Development

Documentation and understanding of heat transfer effects with a double row of tubes was expanded to examine the front and rear row heater tube interaction. Tests were conducted with single rows (front or rear) and with the normal double row heater. Results indicate that the addition of the rear row enhances

heat transfer to the front row, whereas addition of the front row reduces heat transfer to the rear row at low Reynolds numbers.

A flow distribution rig, or fixture, is in preparation to test flow distribution in the various Mod II heater quadrants. Distribution in each heater tube will be measured as well as distribution into the cylinder and regenerator spaces. These tests will be conducted on the first-build heater quadrants early in PY 1986.

#### Materials Development

Fatigue testing of key Mod II components was conducted in this report period. The components were: prototype heater head casting, piston rod/base joint, and glass wrapped aluminum hydrogen storage bottle. The heater head casting was fully machined with stub tubes installed. It was tested to failure at 771,000 cycles with the failure occurring in the manifold neck. This prototype head had a wall thickness of 5 mm in this region, whereas the final design has a 7 mm thick wall. This result confirms analytical predictions for the prototype design. The piston rod/base joint survived fatigue testing well beyond 100% load conditions, completing  $.15 \times 10^6$  cycles at 160% load before testing was stopped due to rig fixture problems. A problem area other than the rod/base joint was discovered during the test when a failure occurred at the P(min) venting hole in the crosshead area. A revised design with a hemispherical P(min) venting hole will be evaluated in a follow-on test. The hydrogen storage bottle was successfully tested to 10 million cycles at pressure cycled from 18 to 20 MPa, and is considered acceptable for use in the Mod II system.

#### Seals Development

Endurance tests were conducted to evaluate seal life for two different configurations, the standard PL seal and the pumping-ring seal. In a 2000 hr CVS type



test in engine No. 6, PL seals were installed. Two of the seals completed 2000 hrs of testing with no problems. The third seal was replaced at 270 hrs, with the replacement completing the additional 1730 hrs without incident. The fourth seal was replaced several times during the test, with five seals required to achieve 2000 hrs.

This seal was on cycle No. 4, nearest the hydrogen compressor. Engine No. 6 also used the reduced diameter journal bearing drive (more flexible crank shaft) which is not common to the Mod I engines. The reduced journal drive, in conjunction with the compressor loading, has resulted in deflections which could explain the short seal life in cycle No. 4. The pumping-ring seals were installed in engine No. 7 for a similar test to 1000 hrs. All four seals failed at 272 hrs and three of the replacement seals failed after they accumulated 543 hrs. The reason for this poor performance is not clear since good experience was obtained in P-40 engines.

Endurance tests were conducted to evaluate both split-solid and single-solid piston ring configurations in the CVS duty cycle. Successful engine tests of 2000 hrs were run for both piston ring sets. Performance testing was also conducted to compare the two ring sets. Preliminary indications suggest improved efficiency can be obtained with the single-solid rings.

Cold room tests were conducted with a full Mod I SES to evaluate Bill of Material (BOM) Viton O-ring seal leakage at low temperatures. Tests down to  $-20^{\circ}\text{C}$  showed no increase in leakage. While lowering temperature to  $-30^{\circ}\text{C}$ , a very high leakage developed, most probably in the external plumbing. The test will be repeated with alternate O-ring materials.

### Controls and Auxiliaries Development

Major activity in the controls and auxiliaries area was directed at checkout of

Mod II type systems using currently operating Upgraded Mod I engines. Basic checkout was conducted using the test cell engine (Upgraded Mod I engine No. 5) at MTI. All Mod II systems were checked out with the exception of the three volume hydrogen compressor. Functional operation was achieved for the DAFC, electric atomizing air compressor, electrically-driven blower and alternator, electrically-actuated PCV, and the two-tank hydrogen storage system. Following checkout in the test cell the components were installed, one at a time, except for the electric drive blower and alternator, in the Spirit vehicle (Upgraded Mod I engine No. 8). Checkout in the vehicle was accomplished via local driving, using the New York State (NYS) Encon vehicle dyno, and also the Mercedes Benz Facility. Highlights of this checkout phase are noted in the following section, "Mod I Engine Test Program".

In the test cell, the DAFC provided stable engine operation over the entire engine operating range. A lower idle fuel rate (.2 g/s versus .35 g/s) was achieved relative to K-Jetronic control. A higher maximum power was achieved with the DAFC with a CGR combustor due to the lower system pressure drop achieved with the DAFC. To achieve faster ignition times, a reduced atomizer airflow was successfully incorporated during the engine start-up phase. Finally, stable, responsive combustion airflow was achieved by the electric drive blower without the use of an air throttle.

In the vehicle, a series of EPA driving cycle tests was conducted at the Mercedes Benz Facility to evaluate the DAFC. Throughout all the tests, vehicle emissions remained low and combustion system excess air ratio was very stable, much better than with the K-Jetronic system. An additional benefit was also demonstrated on the vehicle dyno at Encon. Engine power level under heavy load was higher with the DAFC due to its ability to maintain heater set temperature.

## Mod I Engine Test Program

The focus of the Mod I engine test program has been centered on development of Mod II technology. A total of 2827 hrs of operation were accumulated during this report period, bringing total Mod I hours to 14,239.

Mod I engine No. 3 was devoted to EHS development, testing the CGR combustor and nozzle/atomizing air system, as noted in the EHS discussion.

Upgraded Mod I engine No. 5 was devoted to development of Mod II systems. The control and auxiliary components for the Mod II were checked functionally on the engine installed in the dyno cell, and preliminary transient checkout was also accomplished. The units tested were: electrically-driven atomizer air compressor, electrically-actuated PCV, DAFC, electrically-driven blower, and the dual voltage high efficiency alternator. All systems functioned acceptably in the test stand. The only problem encountered was repeated electronic control circuitry failures in the blower drive system. Final transient development and optimization will be conducted in the Spirit Upgraded Mod I installation.

Performance tests to evaluate the single-solid piston ring for Mod II use were also conducted on this engine. Preliminary results indicate that the single-solid piston rings provide improvement in engine net efficiency over the full range of engine operation. A more detailed analysis and an assessment of durability/repeatability is required to finalize the decision to include single piston rings as BOM for the Mod II.

Upgraded Mod I engine No. 6 was utilized to conduct endurance testing for the BSE at 820°C. Total CVS cycle endurance time of 2000 hrs was reached during this period, with 1134.5 hrs accumulated during the latter half of 1985. Results were encouraging. Very few hardware problems were encountered; the only major changes

required were a cylinder liner O-ring, combustor, flamestone, and one main seal. There was no measurable performance deterioration over the entire 2000-hr endurance period.

Mod I engine No. 7 conducted seals and piston ring endurance. As noted in the seals development section, the pumping ring main seals suffered several failures, in marked contrast to prior positive performance in P-40 engines. Single-solid piston rings functioned without problems in this period and continue to run in the engine.

Upgraded Mod I engine No. 8, installed in the Spirit vehicle, was used extensively to develop and optimize several Mod II components, specifically the DAFC, electrically-actuated PCV, CGR combustor, atomizing air system, and Mod II potential fuel nozzles. These components were installed one at a time, and functional checkout and preliminary optimization completed on each component prior to installation of the next one. Vehicle dynamometer testing was conducted at the Mercedes Benz Facility in Ann Arbor, and confirmed improvements in performance and emissions with the DAFC system.

Upgraded Mod I engine No. 9 was refurbished for use as a generator set engine to be evaluated by the U.S. Army. The engine was rebuilt and acceptance tested as part of the ASE Program. Installation and integration with the generator set was supported by funding sources outside the ASE Program. The U.S. Army evaluation will consist of performance and endurance testing.

## Mod II Engine

### Mod II Design

The major designs for the basic Mod II engine were completed and discussed in the previous Semiannual report (SA8). Design efforts in the latter half of 1985 focused on design of key systems components, the PCV, and hydrogen compressor, and also on processing of engineering

change notices (ECNs) to correct problems encountered in manufacturing and assembly of the BSE. The designs of the PCV and compressor were completed during this report period; 89 ECNs affecting 162 drawings were issued.

#### Mod II Analysis

As a follow-up to extensive analytical effort performed during the Mod II design, documentation of computer codes formulated during that period was initiated. A key analysis, that of the losses which occur in the appendix gap region of Stirling engines, was documented and released in December.

Testing of an annular version of the P-40 engine was conducted to evaluate partition wall losses with three different partition wall configurations. Results obtained exhibited problems with data scatter and repeatability. Potential leakage problems were identified and a design modification completed to alleviate the leakage. Testing will continue in 1986 to complete the test series.

Baseline performance and fuel economy were determined for manual transmission- and automatic transmission-equipped Celebrity vehicles, the baseline Mod II vehicles. Driving cycle fuel economy

agreed very well with EPA-published figures. Acceleration tests were very repeatable and seemed to give reasonable times, therefore they will be used for IC baseline comparisons.

#### Mod II Hardware

Hardware for the first build of the Mod II was procured during this report period and engine assembly begun. The first engine will incorporate an analog block (machined from steel instead of cast iron) and limited pressure heater heads due to problems encountered with the castings. These items are compromises to allow early functional testing of the BSE.

Work planned for the next report period (January-June 1986) includes:

- Complete build of the initial Mod II BSE and begin testing in the MTI dyno cell.
- Procure Mod II SES hardware in preparation for Mod II SES testing.
- Complete functional assessment of Mod II control/auxiliary systems.
- Continue endurance testing to validate seal and piston ring life, and engine integrity at 820°C set temperature.

## II. REFERENCE ENGINE SYSTEM DESIGN

This task was re-activated in this report period to address two areas: 1) update of the 1983 RESD to incorporate new technologies that have emerged since the 1983 RESD was configured; and, 2) to investigate larger size Stirling engines and identify potential applications in the transportation arena. Work accomplished in this time period included assessment of two potential application areas for the higher power engines, and preparation of preliminary estimates of performance and geometry for a 100 kW version of the Mod II engine.

To expand the applicability of Stirling engines in the transportation arena, two applications investigated were heavy duty line haul trucks and city bus/delivery van. The former was selected for evaluation since it is the largest user unit of transportation energy following the personal auto. The latter was chosen as a result of a current program with the U.S. Air Force to evaluate an Upgraded Mod I engine in an Air Force Van.

A study of the heavy-duty application revealed that the application is primarily driven by life cycle cost. The important line haul truck parameters are listed in Table 2-1. A simple engine-oriented life cycle cost model is shown in Table 2-2. It is apparent that the major contributor to life cycle cost is fuel cost, or engine BSFC. It has been concluded that although some potential benefit could be gained from a Stirling engine in this application, the development required (in terms of time and funding) is such that the probability of it occurring is probably low until the engine is proven in some other commercial application.

The bus/van application appears to have benefits that can be achieved in a more near-term time frame. Emissions and noise in urban areas created by diesel power plants in these applications are becoming a concern. The Stirling engine offers greatly reduced emissions and noise potential. Further, there has been considerable activity to convert existing bus/van/light truck fleets to operation on propane or compressed natural gas. This is a good application for the Stirling engine due to the ability to operate easily on gaseous fuel while providing fuel economy improvement relative to a gas-converted, spark-ignition engine. In this application, when natural gas is compressed for fueling of the tanks, a compressor 100 hp or less is typically used. Here again there is a potential for the Stirling engine (specifically the Mod II) to be utilized as the compressor power source, utilizing natural gas as its fuel. This application will be further investigated in the next report period.

To obtain estimates for the higher power Stirling engine, scaling studies are underway for two concepts, the Mod II-type V-annular, and an air engine originally conceived for a military tank installation. Preliminary results have been obtained for a 100 kW Mod II-type engine. The performance is shown on Figures 2-1 and 2-2, and a layout with overall dimensions is shown on Figure 2-3. Note that the efficiencies shown are several points better than projected Mod II levels of 38.5%. This concept will be refined and scaled up further in the next report period. The air engine performance and geometry will also be defined.

TABLE 2-1

LINE HAUL TRUCK SYSTEM PARAMETERS

(from most important to least important)

1. Life Cycle Cost - Minimizing life cycle costs is key to operator profit.
2. Emissions - If proposed federal regulations are maintained, current diesel technology indicates that expensive particulate traps would be required to meet particulate regulations.
3. Packaging - Current emphasis in truck development to improve fuel economy is focused on truck aerodynamics. To be competitive with existing diesels, alternate power plant/drive trains must package at least as well as existing systems.
4. Fuel - Diesel fuel is the infrastructure-demanded choice. Current trends toward a deterioration in fuel quality (lower cetane number) may provide problems for diesels.
5. Weight - Weight reduction is important only if truck is weight limited. Few are, although most are volume limited.

TABLE 2-2

SIMPLE LIFE CYCLE COST MODEL (ENGINE RELATED)

Assumptions:

- 500,000 miles to first overhaul
- 350,000 miles after overhaul to end of life
- 150,000 miles/year
- 5 mpg fuel economy
- \$1.00/gallon fuel cost.

Life cycle cost =  $\Sigma$  (purchase price + maintenance cost + overhaul + cost fuel cost)

• Purchase price	\$ 15,000
• Maintenance cost \$3,600/year + 5.7 year	20,500
• Overhaul cost	5,000
• Fuel cost 850,000 miles/5 mpg x \$1.00/gal	170,000
<b>Total</b>	<b>\$210,500</b>

Significance of fuel economy:

1% pt BSFC (.34  $\rightarrow$  .33) = \$5,000 LCC  
= 2.4% LCC

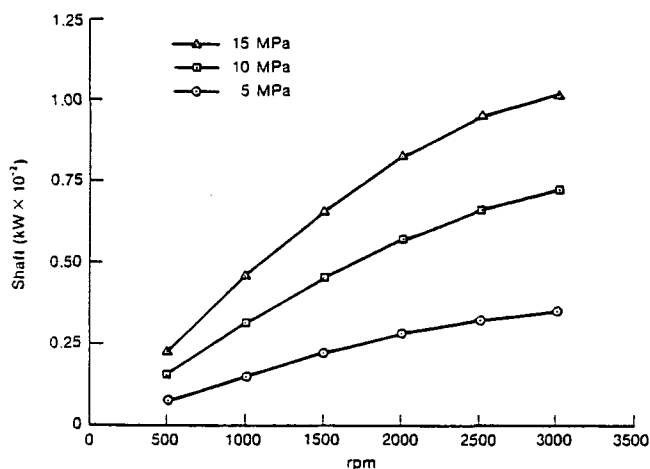


Fig. 2-1 100 kW RESD Net Power

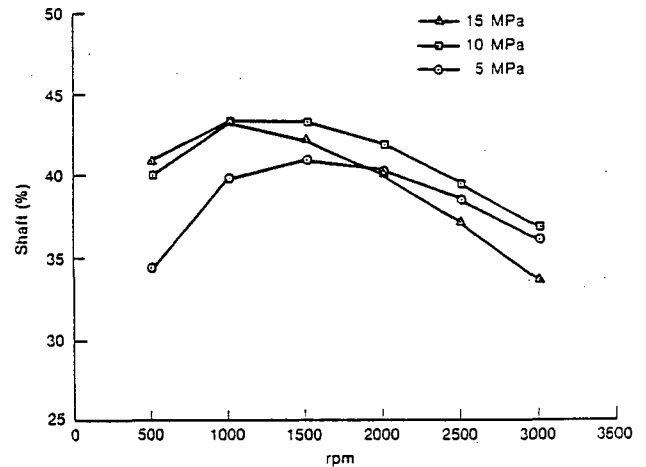


Fig. 2-2 100 kW RESD Net Power

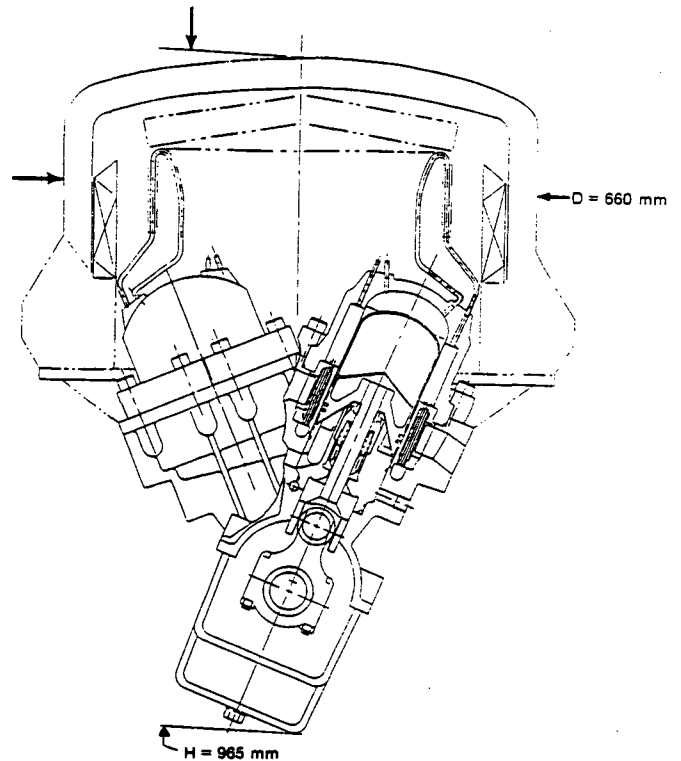


Fig. 2-3 100 kW RESD Cross-Sectional Layout

### III. COMPONENT AND TECHNOLOGY DEVELOPMENT

#### External Heat System

The primary goal of the EHS is low emissions while maintaining high efficiency for a 30:1 fuel turndown ratio in a minimum volume.

The design must consider durability, heater head temperature profile, and expected use of alternate fuels while recognizing the significant cost impact of system size and design.

Major activities during the latter half of 1985 were Mod II combustion system performance, EHS transient analysis, CGR combustor durability, Mod II fuel nozzle/igniter development, alternate fuel/conical nozzle development and ceramic preheater development.

#### Mod II Combustion System Performance

The objective of Mod II combustion system performance is to meet the program emissions goals (g/mi):

NO <sub>x</sub> :	0.4
CO:	3.4
HC:	0.41
Particulates:	0.2

with soot-free combustion (Bacharach  $\leq 2$ ), low heater head temperature variation ( $\Delta T \leq 100^\circ\text{C}$ ) over a 30:1 fuel turndown ratio. In order to meet the NO<sub>x</sub> requirement, CGR is used. Early development of the Mod II 12-tube CGR combustor and BOM fuel nozzle was conducted with Mod I hardware. Compared to Mod I, the Mod II EHS design features a number of changes which impact performance (Table 3-1).

In order to optimize performance, tests were conducted at simulated Mod II condi-

tions using Mod I rigs and engines. Results of the tests with partially blocked heater heads to simulate Mod II heater head  $\Delta P$ s indicated a detrimental effect on NO<sub>x</sub> emissions (Figure 3-1)\*. In this test, case No. 2 is felt to be the closest simulation of Mod II aerodynamics and heater head  $\Delta P$ . Reduction in atomizing airflow to 0.4 g/s results in decreased CGR (Figure 3-2) and, hence, increased NO<sub>x</sub> emissions (Figure 3-3). The increases in NO<sub>x</sub> can be somewhat offset by using exhaust gas in place of air for the atomizing fluid (Figure 3-4). The beneficial effect of exhaust gas on NO<sub>x</sub> also applies regardless of the heater head  $\Delta P$  (compare Figure 3-5 to 3-1).

TABLE 3-1

#### PERFORMANCE IMPACT OF MOD II CHANGES ON EHS PERFORMANCE

<u>Item</u>	<u>Impact</u>	<u>Expected Result</u>
Increased Heater Head $\Delta P$ (0.6 vs 0.3 KPa)	Reduced CGR	Increased NO <sub>x</sub> , CO and Soot
Atomizing Airflow (0.4 vs 1.0 g/s)	Increased Temperature and Residence Time	Increased NO <sub>x</sub>
	Poorer Mixing	Increased Soot
Idle fuel flow (0.15 vs 0.25 g/s)	Combustion Stability	Increased CO and HC

An analysis was performed, using the Mod I data previously cited, to predict Mod II NO<sub>x</sub> emissions. Using a range of data typical of Mod I, it was concluded that the increase in NO<sub>x</sub> due to heater head pressure drop (Figure 3-6) can be compensated for by using exhaust gas atomization (Figure 3-7). The scatter band evidenced in these two figures represents variations in the condition of individual combustors, nozzles, and preheaters, and possibly engine-to-engine variations.

\*Figures can be found at the end of this section beginning on page 3-16.

The dominant effect on Mod II is, however, the increase in NO<sub>x</sub> caused by the reduction in Mod II atomizing flow (Figure 3-3). The net result is a predicted Mod II NO<sub>x</sub> emissions of 0.7-1.0 g/mi. Although higher than the goal, NO<sub>x</sub> still conforms to 1987 EPA requirements (1.0 g/mi). It should be noted that the apparent large reduction in NO<sub>x</sub> emissions, seen on the Mod I with exhaust gas atomization (Figure 3-4), is not as beneficial to Mod II. This is because most of the Mod II CVS cycle occurs at fuel flows less than 0.5 g/s where the impact of exhaust gas atomization on NO<sub>x</sub> is much less significant.

Reduction of atomizing airflow to the Mod II goal of 0.4 g/s also leads to unacceptable soot levels. Regardless of whether the current 12 orifice, or a reduced number of orifice, BOM nozzle is used, the Bacharach <2 goal is exceeded (Figure 3-8). With 12 orifices, A/F momentum decreases with atomizer flow. By reducing the number of orifices, momentum can be maintained. In order to reduce soot, nozzle cooling and reduction in orifice diameter will be evaluated in PY 1986. The expected increase in CO and soot with heater head pressure drop and CO and HC at Mod II idle fuel flow did not occur, indicating adequate combustor mixing intensity and stability. Exhaust gas atomization had no appreciable influence on soot or CO emissions.

### EHS Transient Analysis

The purpose of transient analysis is to develop predictive techniques which will enable vehicle performance to be optimized. The analysis addresses start-up effects, interaction with the A/F and temperature control systems and techniques for predicting transient CVS cycle emissions based on steady-state results.

Start-up optimization tests were begun with the Upgraded Mod I/Spirit equipped with a CGR combustor, BOM nozzle and DAFC. The objective is to determine the optimal lambda, atomizing airflow, and fuel flow ramp rate that will minimize

drive-away time, fuel flow, and CO/HC emissions. Previous results have indicated drive-away time is longer with CGR versus EGR, 103 versus 65 sec, increasing the need for optimization with the Mod II CGR system. This study will be completed during the first half of 1986 at room and cold ambient temperature.

The contribution of soot to vehicle particulate emissions was determined during testing at the NYS ENCON dynamometer facility. Two fuel nozzles were used with extremely low atomizing airflows to purposely generate high soot (smoke) numbers during transient portions of the CVS cycle. No correlation was found between soot and particulates (Figure 3-9), indicating soot is not a major particulate constituent. Furthermore, complete CVS cycle tests revealed that soot is not a concern in meeting the Program particulate goal of 0.2 g/mi (Table 3-2). Regardless of the relative smoke readings, particulates were < 0.1 g/mi. Soot is still of concern, however, because of its influence on preheater plugging and esthetics (smoke-free exhaust).

TABLE 3-2  
RESULTS OF COMPLETE CVS-CYCLE TESTS  
(PHASE I, II, AND III)

Test Date	Particulates Weighted (g/mi)	Warm-Up Times*		Relative Smoke No.	
		Cold Start (sec)	Hot Start (sec)	Φ1 + Φ2	Φ3
10/10/85	0.080	108	--	100	100
9/26/85	0.016	--	--	39	63
9/10/85	0.033**	107	45	38	4

Warm-up time = time from fuel valve on, until mean rear tube temperature (MRTT) = 700 °C

$$\text{Weighted g/mi} = 0.43 \frac{\text{grams } (\Phi 1 + \Phi 2)}{\text{miles } (\Phi 1 + \Phi 2)} + 0.57 \frac{\text{grams } (\Phi 3 + \Phi 2)}{\text{miles } (\Phi 3 + \Phi 2)}$$

\* Atomizing air at 3 psi for ignition, increased to 7 psi when tube temperature = 700 °C

\*\*Rust appeared in "B" probe during test, reading probably too high.

Past attempts to predict CVS cycle emissions, using steady-state engine data, have resulted in NO<sub>x</sub> and CO/HC emissions which were 15% too high and an order of magnitude too low, respectively. In both cases, the low tube and preheat air temperatures which occur during start-up were felt to reduce NO<sub>x</sub> and increase

CO/HC over that seen during steady-state testing. This impact of start-up on emissions has been observed during CVS cycle tests. In order to quantify the effect of tube temperature on emissions, a parametric test was performed on Upgraded Mod I engine No. 5. Set temperature was varied from 535 to 820°C at the low fuel flows encountered during start-up. Variations in NO<sub>x</sub> and HC emissions were as expected (Figures 3-10 and 3-11). The magnitudes of the changes in CO and soot emissions, while in the anticipated direction, were less than expected (Figures 3-12 and 3-13). Thus, the high CO levels encountered during vehicle start-up are due more to lambda and pre-heat air temperature as opposed to tube temperature. The effects of tube temperature will be incorporated into the CVS emissions predictive code during 1986.

#### CGR Combustor Durability

The objective of the combustor durability effort is to demonstrate a life of 1000 hrs and 3000 starts. This is an interim goal between the 500 hrs or less life of current combustors and the final program goal of 3500 hrs and 10,000 starts. Durability activities included oxidation-resistant coatings (ORC) and materials manufacturing feasibility. Detailed temperature measurements were made of the CGR combustor and a stress analysis completed.

The EGR combustor with plasma sprayed ORC Amdry 962 and 995 coatings\* has attained 140 hrs of vehicle and engine cell operation without evidence of degradation. The coatings will be microscopically inspected after 300 hrs. A CGR combustor was also coated during this report period (1/3 Amdry 962, 1/3 Amdry 995, 1/3 base). It will be installed in engine No. 6 for endurance testing. At 1000 hrs a detailed inspection will be performed. Trial drawings of textured 310 stainless steel (Mod II material), 253 MA and Cabot

214 (Upgraded Mod I combustor shells) were successfully accomplished.

Rig temperature mapping tests were completed, using a Mod I CGR combustor, with and without a flame shield. Although the shield reduces the absolute temperatures (Figure 3-14), stress levels were not affected. Small differences in temperature were noted between the shaded area above and exposed area between the mixing tubes, indicating a nonluminous flame. The axisymmetric analysis concluded that the highest stress levels occur near the constrained inner and outer diameters. The Mod II CGR combustor allows axial movement at the inner diameter and, hence, will have acceptable stresses.

#### Mod II Fuel Nozzle/Igniter Development

The objective of nozzle/igniter development is to reduce atomizing airflow to 0.4 g/s (Mod II goal), eliminate plugging, extend igniter life to 200 hrs and manufacture nozzles which will limit flow variations so that repeatable emissions and heater head ΔTs may be obtained.

The impact of reduced atomizing airflow and idle fuel flow on emissions has been discussed under "Mod II Combustion System Performance". A detrimental side effect is an increased tendency of the nozzle to plug at low flows. This was confirmed during performance rig testing of an instrumented nozzle (Figure 3-15) where reductions in atomizing air (Figure 3-16) and fuel flow (Figure 3-17) cause A/F mixture and nozzle temperatures to increase, thus increasing the likelihood of fuel pyrolysis inside the nozzle. Another potential problem is the degradation in smoke number which results from a leaking fuel nozzle (Figure 3-18). Leakage, which results from nozzle disassembly/reassembly needed to clean a plugged nozzle, leads to excessive soot which in turn causes preheater plugging and degraded engine performance. Thus, the ob-

\*See SA8 for composition



jective of reducing atomizing airflow must address plugging and leakage as well as emissions.

In order to eliminate plugging, two parallel approaches were taken, active and passive cooling. In the first case, three nozzle bodies, surrounded by a water cooling jacket were designed. The bodies differ only in the area of the metering orifices; 4.62 mm<sup>2</sup> (current BOM), 2.75 mm and 1.13 mm<sup>2</sup>. During 1986 these nozzles will be fabricated and tested to determine the optimal cooling rate at various reduced atomizing airflows. The lowest feasible airflow will be determined from CO and soot emissions. The passive approach involves a thermal barrier coated (TBC) nozzle tip to reduce thermal conduction into the nozzle passages. The yttria stabilized plasma sprayed TBC consists of a 2-5 mil bond coat of Amdry 962 and a 6-10 mil top coat of Metco 202. Two nozzle tips have been coated and a method of drilling the metering orifices is being developed. Both laser and mechanical drilling will be attempted. Tests will be conducted during 1986 with a thermocouple instrumented nozzle to determine the effectiveness of TBC in preventing plugging via reduced internal nozzle temperatures.

The effort to extend igniter life to 200 hrs has been achieved with one igniter achieving over 500 hrs and two others operating well with ~100 hrs of service. The successful center tube igniter (Figure 3-19) replaces the earlier pronged design which repeatedly failed in only a few hours. Tests were conducted to determine if ignition delay had been affected by the change in igniter design. The conclusion was that delay times were similar, with the center igniter being more flexible since it can operate over a wider atomizing airflow range (Figure 3-20).

In order to limit nozzle flow variations, 10 "standard" BOM nozzles were fabricated

with stringent dimensional tolerances and inspection requirements. Nine of these nozzles were assembled and cold flow checked after being modified to incorporate the center tube igniter. Eight of the nine nozzles were found to vary  $\pm 10\%$  in fuel flow (Figure 3-21) and all nine varied  $\pm 3.3\%$  in atomizing airflow (Figure 3-22). This represents a vast improvement over the  $\pm 25\%$  variation typical of earlier BOM nozzles. Cleaning procedures and designation of the standard nozzles as critical hardware (log book required) will ensure that performance is maintained throughout the life of each nozzle. Performance of the entire EHS is expected to be much more consistent as a result. A similar procedure will be followed in 1986 with the Mod II nozzle.

#### Alternate Fuel/Conical Nozzle Development

One of the goals of the program is multi-fuel capability with the proviso that satisfactory performance must first be obtained with unleaded gasoline. The long term object of this task is to ascertain the effect of alternate\* fuels on EHS performance and durability goals and implement design changes, if needed, to accommodate them. During this report period the most difficult of the alternate fuels, diesel grade, DF-2, was tested. The assessment of the degree of difficulty is based on viscosity (atomization), aromatic content (soot), sulfur (pre-heater corrosion), and volatility (ignition and start-up) considerations.

The conical nozzle was selected for use with diesel fuel because of its demonstrated ability to burn a variety of alternate fuels without plugging. This experience was obtained under a separately funded DOE alternate fuels program (DOE Report DOE/CE/50043-1) using unleaded gasoline, naphtha, ethanol, methanol, diesel, and naphtha/diesel blend fuels. The conical nozzle is also an at-

\*Gasohol, diesel (DF-2), kerosene, and home heating oil

tractive alternative to the Mod II BOM nozzle due to the plugging problems of the latter. Hence, a two-fold development effort was conducted using the performance rig. Both gasoline and diesel fuel evaluations were conducted to address Mod II and alternate fuels respectively.

The problem encountered in the past with the conical nozzle was unacceptably high heater head  $\Delta T$  and soot emissions burning gasoline, when combined with a Mod II-type CGR combustor\*. Both nozzle and combustor modifications were made to correct this. The nozzle modification (Figure 3-23) consisted of replacing the single exit orifice in the fuel spin chamber with three holes in order to simulate BOM nozzle axial momentum. The combustor modifications (Figure 3-24) were designed to improve mixing.

Following successful free-burning rig tests, these modifications were tested in the performance rig. The three-hole conical nozzle and unmodified CGR combustor burning gasoline was found to reduce  $\Delta T$  and soot levels (Figure 3-25) compared to the single-hole conical nozzle. These two parameters are also comparable to a plug-free, nonleaking, BOM nozzle and lower if the latter is plugged or leaking. (BOM soot levels  $> 10$  are attributed to leaks). The conclusion was that overall performance was comparable to the BOM nozzle, with the Mod II CGR combustor burning gasoline, and that plugging does not occur, regardless of how much atomizing air or fuel flows is reduced. Soot levels at 0.4 g/s atomizing airflow are, however, too high indicating more development is needed. This is also true of the BOM nozzle as previously discussed.

Diesel fuel testing of the three-hole conical nozzle and CGR combustor indicated higher soot levels than gasoline (Figure 3-26) but equivalent-to-better

than those obtained with the BOM nozzle (Figure 3-27).

Gasoline tests of the three-hole conical nozzle with modified CGR combustors were inconclusive because a heater head leak was discovered after the tests, negating the results. Based on the highly encouraging results obtained without combustion modifications, these tests were not repeated. Three-hole conical nozzle development will continue in 1986 via engine and vehicle transient evaluations.

#### Ceramic Preheater Development

The objective of ceramic preheater development is to demonstrate the feasibility of fabricating low cost ceramic matrices by producing several mixed-oxide preheater blocks which will have less than 5% leakage after 300 thermal cycles.

Attempts by Coors Porcelain Company to fabricate eight blocks were unsuccessful due to unacceptable leakage caused by internal cracking (Figure 3-28). Variations in the low and high firing cycle, orientation of the platelet cut, number of platelets in the fired stack, stack orientation during firing, ceramic loading and the use of virgin, as opposed to reclaimed material, did not significantly affect the formation of cracks. A crack-free 1/3 high stack was successfully fired after varying the amount of the three plasticizers in the binder.

Since progress was made, a purchase order was placed with Coors Porcelain to fabricate two mixed-oxide blocks for delivery in 1986. These will be fabricated after tooling modifications to increase gating at the tip, using the revised plasticizer content binder. The purpose of the gating is to obtain a more uniform platelet thickness which will prevent tip slumpage, another potential cause of cracks.

---

\*Performance with a turbulator type combustor was better but required EGR to be acceptable.

In order to determine the susceptibility of mixed oxide to sulfuric acid attack, samples were placed in the exhaust of the gasoline fired performance rig. No weight loss occurred after 100 hrs.

### Hot Engine System Development

The primary goals of this task for this report period were to develop heat transfer correlations to predict heater head performance of the Mod II and larger engines, to evaluate the pressure drop of Mod II regenerators, and to evaluate the flow characteristics of Mod II heater heads.

#### Heater Head Heat Transfer

The previous Semiannual report (SA8) discussed the results of tests in the double mantle row (DMR) rig. The improved heater head heat transfer for Mod II and the preferred front-tube geometry were detailed. The DMR results with the Mod II rear-row geometry coupled with different front-row geometries, demonstrated that the same test section (identified as number 218) would perform quite differently depending on what it was tested with. A study of these interactions was added to the test plan such that each test section was tested individually in the DMR rig. The following general conclusions were made.

- The presence of the rear row increases the heat transfer to the front row over the range of combustion gas mass flows (1-12 g/s). With a rear row present, significant turbulence is created on the back-side of the front tubes. This turbulence improves heat transfer. Figures 3-29 and 3-30 present results for two representative front row test sections.
- The presence of the front row decreases the heat transfer to the rear row over the range  $20 < Re < 60$ . The front row forces most of the flow into "jets". These jets are hitting the rear row only at a

small portion of the fin, creating inefficiencies. As  $Re > 60$ , the upstream turbulence created by the rear row itself predominates, and there is little negative effect from the front row. See Figures 3-31 and 3-32. When a test was run with an additional 20 mm spacer between the front and rear rows (normal spacing is 18 mm), the performance of the rear row increased (Figure 3-33). This is due to the diffusion of the aforementioned "jets". The distance between the front and rear rows in the Mod II engine is normally 40 mm.

This same DMR rig will be used to investigate the heat transfer parameters for larger ( $\sqrt{6.35}$  mm) tube geometries with fins. The sections were designed at MTI and will be assembled before being shipped to USAB for testing. The objective will be to protect the Mod II development with additional geometries of a generic nature.

The Mod I regenerator  $\Delta P$  rig was modified to evaluate Mod II regenerator matrices prior to the final assembly process.

A Mod II heater head flow fixture has been designed and was procured. Using a static pressure probe rake, flow distributions into the cylinder housing, and into the regenerator area will be determined and evaluated for uniformity. Static pressure taps, attached to every other tube, will be used to evaluate tube-to-tube flow distributions. Both configuration No. 1 (first build with two manifolds), and configuration No. 3 (one manifold) will be investigated.

### Materials and Process Development

The goal of this task is the utilization of low-cost, low-strategic element content materials in the ASE, capable of surviving 3500 hrs of automotive duty cycle exposure. Additionally, this task provides materials support to the Mod II design and component development activities.

Accomplishments during the second half of 1985 include:

- Proof - fatigue testing of the following components:
  - Hydrogen storage bottle
  - Heater head manifold - configuration No. 1
  - Piston rod/base/crosshead
- Heat treat optimization for the Mod II cooler/liner
- Determination of a HIP cycle for XF-818

Activities planned for the next reporting period include:

- Continued proof-fatigue testing of Mod II
  - Heater head castings
  - Control hardware
  - Piston rod/base/crosshead
  - Cast V-block
- Fatigue strength characterization of HIPped XF-818 at room temperature
- Continued optimization of the Mod II cooler liner heat treatment.

#### Mod II Piston Base/Rod/Crosshead Fatigue Test

The goal of this task is the development of a fatigue resistant piston base/rod/crosshead assembly. During this reporting period, testing was done on one additional (the fourth) piston base/rod/crosshead assembly while another was being prepared for test.

The work in the previous report period indicated that an undercut rod/base design would be superior to a chamfered base/rod design. The next test included an undercut on the rod. The radius between the undercut and the rod surface was increased from .05 to 10 mm to reduce the stress raiser. This joint survived into Step 5 of the test cycle shown in Table 3-3 completing  $0.15 \times 10^6$  cycles of

the 160% load. The base/rod joint was still fully serviceable, but testing was discontinued due to fixturing problems.

TABLE 3-3

TEST CYCLE - MOD II PISTON  
BASE/ROD/CROSSHEAD

Step No.	No. of Cycles	% of Full Load
1	$10^7$	100
2	$10^6$	120
3	$10^6$	140
4	$10^6$	150
5	$10^6$	160
6	$10^6$	180

During the previous test, a failure occurred in the crosshead end due to a heat treat crack. The modification to avoid this was to radius the center drill hole to eliminate a sharp stress raiser. This modification requires another test to confirm the new design modification.

The next test will include an undercut rod with the 10 mm radius and with a hemispherical tip center drill hole in the crosshead end. This is being prepared and will be tested early in the next reporting period.

#### Heater Head Manifold Fatigue Test, Configuration No. 1

The purpose of this test is to proof-fatigue test the manifold region of the casting with stresses simulating those at elevated temperature (800°C).

A Mod II prototype heater head (1013 D03-0002) was fixtured to hydraulically proof-fatigue test the manifold and upper dome portion of the casting. The manifold was fully machined and stub tubes were brazed using the standard braze and braze cycle.

The test cycle pressures were determined by multiplying the 100% pressure by the ratio of room temperature to 800°C yield strengths.

$$100\% \text{ load} \times \frac{(y.s. RT)}{(y.s. 800^{\circ}C)} = \text{test load}$$

$$15 \pm 5 \text{ MPa} \times \frac{(415)}{(261)} = 23.8 \pm 7.95 \text{ MPa}$$

A sinusoidal wave form at 10 Hz was used to apply the cycle pressures.

The casting failed in the neck region by fatigue after 771,000 cycles. A failure analysis indicated no anomalies were present and an examination of fracture features and cycles to failure indicated that the manifold stress were  $\sqrt{390}$  MPa maximum, and 195 MPa minimum.

The manifold neck is only 5 mm thick in this prototype casting. This test validates previously obtained analytical results and the selection of the 7 mm thickness for the Mod II in the neck region. The manifold portion will be reworked and testing continued during the next report period.

#### Proof-Fatigue Testing - Hydrogen Storage Cylinder

A 20.69 MPa (3000 psi) rated aluminum/fiberglass wound gas cylinder was fatigue tested for 10 million cycles with pressure cycling between 18 and 20 MPa during the last reporting period. During the current reporting period, the same gas cylinder was pressurized to 64.1 MPa (9.3 ksi) and no damage was noted. The cylinder was accepted for use in the Mod II hydrogen storage system.

#### Cooler/Liner Heat Treat Optimization

The purpose of this test was to determine if it was possible to ion-nitride the stainless steel cooler/liner made from SIS 2324 (AISI 329, or Carpenter 7-Mo Plus) in a temperature range which would not severely embrittle the component.

The test program was separated into two phases. The first phase was to determine hardness response to various temper-

atures and cooling rates. This was accomplished during this report period.

The second phase will confirm the results of the hardness response with Charpy V-notch impact tests.

Several samples were given a simulated braze cycle to put the material in the same condition as the components are prior to ion-nitriding. Then individual samples were subjected to various temperatures used in ion-nitriding and cooled quickly. The result indicated that embrittlement does not occur after 10 hrs at 535° to 590°C.

What was discovered, however, is that embrittlement can occur during cooling through the 535° to 370°C temperature range. The amount of embrittlement is proportional to the time in the embrittling temperature range. It was determined that parts must be cooled to below 370°C within  $\sqrt{10-15}$  minutes to avoid embrittlement as determined by hardness.

The next phase will be to determine how much embrittlement does occur during the different cooling rates and how much impact it will have on the performance of the component. This will continue during the next report period.

#### Fatigue Strength Enhancement - XF-818

The room temperature fatigue properties of XF-818, heater head casting alloy, were determined during the last half of 1984. It was determined that each of the fatigue crack initiation sites in the fatigue test specimens was associated with microporosity. A further task was initiated to determine what increase in fatigue endurance limit could be achieved by eliminating microporosity with HIP (hot isostatic pressing).

During this report period, work is being done to determine the proper HIP cycle which would "heal" microporosity while not substantially altering the microstructure. Testing will be initiated during the next report period.

## Cold Engine System (CES) Development

The primary objective of CES activity is to develop reliable, effective, long life rod seals, piston rings, and static seals. Development activity during the second half of 1985 was mainly directed at endurance testing of main seals and piston rings in engines. A limited amount of cold leakage data was also generated.

Seal and piston ring development will continue in 1986 mainly through engine tests. Static sealing will be investigated under cold room conditions using a motored engine and the effectiveness of piston ring seals will also be measured during cold starts.

### Main Seals

Endurance/life testing of main seals has continued in Mod I engines No. 6 and 7. Both engines operate on an automated CVS type duty cycle shown in Figure 3-34.

In engine No. 7, Rulon J pumping ring seals were subjected to a 1000 hr endurance test. All four original seals had to be replaced after 272 hr due to oil leakage. These were replaced by pumping rings with increased rod/seal interference. After an additional 543 hr, three of these seals had to be replaced again due to oil leakage. Through the end of the test there was no further oil leakage, although gas leakage to the crankcase was high in the final stages. Measurements of failed seals showed that the bores had deformed to produce a geometry which would be favorable for pumping oil into the seal housing. The reasons for this are not clear, particularly after the previous good experience with this type of seal in P-40 engines.

In engine No. 6, BOM Habia PL seals were subjected to a 2000 hr endurance test. In cylinders No. 1 and 2 the seals completed the test with no indication of oil leakage in the absorption filter however, at teardown, oil was found in both seal housings and cylinders. In cylinder No.

3 the absorption filter indicated oil leakage after 270 hrs and oil was present in the seal housing. The replacement seal completed the test with no further indication of oil leakage, however, at teardown oil was found in the seal housing and cylinder. In cylinder No. 4 the absorption filter indicated oil leakage after 270 hrs and oil was present in the seal housing. The replacement seal ran for 769 hrs when the filter again indicated oil leakage. Again, oil was found in the seal housing and cylinder. A third seal ran for 173 hrs before the filter again indicated oil leakage. A fourth seal also failed due to oil leakage after 856 hrs. A fifth seal ran for 242 hrs before the test was completed. There had been no indication of oil leakage, although oil was found in the seal housing and in the cylinder. The consistently short life of seals in cycle No. 4 suggested that this might be related to the hardware in that cycle but inspection did not reveal any significant differences compared with the other three cycles. This type of failure pattern had not been seen with any other Mod I engines. One major difference is that the crankshaft bearings in engine No. 6 are smaller in diameter than in other Mod I engines. No. 4 cycle is also adjacent to the hydrogen compressor and it was suspected that this, coupled with the smaller bearings might have accentuated the crankshaft bending in the region of cycle No. 4 and adversely affected the crosshead/rod motion. Some limited deflection measurements showed that this was a distinct possibility. This will be investigated further by comparing predicted bending deflections for crankshafts with small and large diameter bearings taking into account both compressor and power piston loading.

In larger piston rod diameter applications, a compound seal of the form shown in Figure 3-35 has demonstrated good performance. To investigate this further, a compound seal was designed for a 15 mm diameter piston rod and two seals were tested in the exploratory rig for a period of 100 hrs. Gas leakage from one seal

was higher than desirable, and gas leakage from the other exceeded measurement capabilities. On the positive side, neither seal leaked oil.

### Piston Rings

In engine No. 6, a set of BOM split-solid, piston rings completed 2000 hrs of CVS endurance cycle testing (see Figure 3-34) without failure and without any deterioration in engine performance. The same rings will be reinstalled in the engine and continue to failure.

In engine No. 7, a set of single-solid rings with the form shown in Figure 3-36 completed 2000 hrs of CVS duty cycle testing without failure. There was also no deterioration in engine performance. The test was terminated at that time to allow the engine to be used for other purposes. During the test period, wear of the single piston rings (loss of weight) ranged from 4-10%.

In engine No. 5, back-to-back tests were carried out to compare the performance of single-solid piston rings with BOM split-solid piston rings. For these tests the single-solid piston rings were mounted in grooves in the bases of the piston domes. With the two ring systems there was no significant difference in the power developed by the engine, however, the single piston rings gave substantially higher efficiency as shown in Figure 3-37. Subsequent tests suggested that part of this improvement might have come from the reduced appendix gap length with the single rings located in the higher position.

### Static Seals

After completing a 1000 hrs test run, engine No. 7 was transferred to a cold room to make gas leakage measurements. Leakages into the water jacket and crankcase were measured using a water displacement method and total leakage was determined from changes in bottle pressure. Leakage measurements were made at +20°, +10°, 0°, -10°, and -20°C. Leakage into the water

jacket was zero throughout. Leakage into the crankcase decreased progressively 0.3 Nℓ/hr at +20°C to 0.001 nℓ/hr at -20°C. Total leakage remained reasonably constant. Attempts to make leakage measurements at -30°C were not successful. Before the temperature had been stabilized, the total leakage suddenly increased to a level at which the pressure could not be maintained. From this, it appears that -20°C probably represents the lower limit at which the BOM, Viton O-rings can maintain an effective gas seal. Further cold tests are planned to evaluate alternative O-ring materials.

### **Controls System/Auxiliaries Development**

The major goals of this task include the development of the engine control and auxiliaries systems. Specific control systems goals include the development of a highly flexible DAFC with a low combustion-air pressure drop and low minimum fuel flow; development of a simplified mean pressure control (MPC) that does not require a servo-oil actuator; development of a high-efficiency combustion air blower and alternator; and, development of logic to control each of these actuators optimally. The hardware designs for each task must be compatible with the extremes of an automotive operating environment.

During this report period a major series of controls and auxiliaries tests was performed on test cell engine No. 5 (Figure 3-38). By the end of the year, 18 of these had been completed with the remainder to be finished in 1986.

### Combustion Control

Considerable evolution of the DAFC occurred during this report period. It started with a tentative design that used automotive pulse width modulated (PWM) fuel injectors as fuel metering valves. The selected valves were first tested in the MTI performance rig. Operating at 20 Hz produced no effect on temperature spread or emissions. Drawings were prepared and reviewed during this time for a

Mod II system. The major components are an air mass flow meter, the digital engine control (DEC) to map out the fuel needed, dual PWM valves, a driving circuit for the valves, and two pressure regulators to keep the  $\Delta P$  across the valves constant.

In October, the new DAFC was installed along with a CGR combustor into the MTI test cell on engine No. 5. Fuel flow meters were precisely calibrated; airflow meters were checked; and, a new blower map, appropriate to the less restrictive DAFC, was set up. Keyboard lambda adjustability was unequivocally demonstrated by producing flat lambda maps of 1.35, 1.25, and 1.15 as measured by emissions equipment. Transient performance was also tested for step changes of combustion flow. Figure 3-39 shows, in an expanded scale, the extremely good emission responses. With these tests, we are probably reaching the limit of what any A/F control system can do, given the limits of the combustor and nozzle flow dynamics.

The new DAFC permitted a wider engine operation range. The Mod I blower was not capable of bringing in enough air to sustain temperature at maximum power with both a CGR combustor and a restrictive K-Jetronic. With the less restrictive DAFC's air system, however, maximum power could be attained. As well, on the low end, the DAFC permitted low idle operation to 0.2 g/s, while the K-Jetronic could not maintain a fuel flow below 0.35 g/s.

An electrically-driven atomizing air compressor was installed in the cell with an automatic upstart valve. The valve permitted reduced atomizing airflow at start-up for rapid ignition. Both the compressor and valve performed well for all starts and over varying fuel flows and lambdas. A smaller (rotary vane) compressor was tested using exhaust gas for fuel atomization. Testing was carried out on the Spirit vehicle with an EGR combustor. The compressor survived the higher temperature operation while

the lower oxygen content reduced NO emissions. Selection of compressor type, flow and pressure requirements will be made after further chassis dyno testing.

In December, the electrically-driven blower was used to pump combustion air for the cell engine. A Mod II temperature control was used for the first time to directly control airflow through proportional and integral blower speed control without an air throttle. DEC values were roughed in to permit initial testing. Further specific development work is also reported in the Auxiliaries Development sections.

Also in December, a Mod II DAFC was installed in the Spirit along with an electrically motor-driven atomizing air compressor and a CGR combustor. Extensive testing of this system was carried out at the nearby NYS Automotive Emissions Lab. 43 tests were carried out in 3-1/2 days. 10 were specific to setting up and checking lambda, the blower map, PID gains, low end DEC resolution, and engine health. Five tests were standard cold start 505s (phase 1 of the EPA urban cycle). 20 were hot-start 505s. Two were phase 2 urban cycles, and 6 0-60 mph accelerations were carried out. During these tests flat lambda maps of 1.25 and 1.15 were used. Figure 3-40 compares the lambda provided by the Mod II DAFC with earlier Mod I K-Jetronic performance over identical cycles. The traces indicate a substantial improvement.

As an early indicator of eventual Mod II control potential, an anticipatory temperature control was manually implemented during some of the Spirit testing. Figure 3-41 compares tube temperature traces over a cycle with normal operation and with a very rudimentary anticipatory control. The traces indicate a substantial potential for improvement is available. In general, the DAFC performance was excellent. It permitted rapid cold starts, greatly improved lambda control, better idle control and reduced air side flow restriction.



The Spirit will be tested at the Mercedes Benz Laboratory in January to further substantiate the DAFC performance and to perform atomizing airflow and compressor tests.

Prototype low temperature, lean burn, exhaust gas (EGO) sensors were received. Sensors from NGK were installed in the cell engine, sensors from Bosch were used in the Spirit. Both look promising, though more characterization will be needed in 1986.

#### Control System Analysis

Full software support for test cell and Spirit development activities was provided. DEC software modifications for Mod II controls and auxiliaries development was successfully designed, integrated, debugged, and documented (flow charts, etc.). Modifications include: head temperature control with feed forward control and electrically-driven blower air delivery system, electric PCV, and MPC with a two-tank system. Each of the above modifications has been successfully tested in the test cell and/or Spirit environment.

A low order, operating point dependent Mod II transient simulation has been completed and debugged on MTI's IBM mainframe. Additional model enhancements with goals of improved model accuracy, without operating point dependence have also been completed. These include a complete engine pressure dynamics model, and an EHS thermal model. Documentation for these models has been completed. The integration of the enhanced model into the transient simulation is still in progress.

Mod II transient simulation has been transferred to an Apple Macintosh computer to fully exploit the graphics capabilities and interactiveness of the personal computer. Model debugging on the Macintosh is currently in progress.

A reduced order multivariable transfer function model for the Mod I engine proc-

ess has been defined. A test plan for data collection required for model development was developed. DEC software modifications required for the test support were implemented, and engine tests were performed, all in late 1985. Model data reduction is currently in progress to permit effective control system design efforts.

Control system gains were optimized for Mod II temperature control using the electrically-driven blower operating on an Upgraded Mod I engine No. 5 in the test cell.

Controls Engine Support - There was a minimum amount of support activities required throughout the reporting period. The single item of significance was the Army generator set, which required ASE test cell re-wiring for acceptance tests.

A set of DEC printed circuit boards was checked out, EPROM's were installed, and the system was sent to USAB in support of testing difficulties encountered there.

Other support activities included re-calibrations, instrumentation installation, and wiring modifications.

An IBM PC Data Acquisition System (DAS) was modified to test a raised appendix gap modification to the Mod I BSE. This system was used to gather per cycle pressure versus crank angle waveform data, as well as to extract phase information in order to obtain efficiency gains.

#### DEC

Hardware and software modifications to the DEC were designed and implemented to support the installation of the following new components on the SES:

- High-level P(max) pressure transducer
- High-level, high-tank pressure transducer
- High-level, low-tank pressure transducer
- Cold junction thermistor

- Atomizing air compressor
- Atomizing air bleed valve
- Tank shut-off valve
- Low tank valve
- Electrically-driven blower control
- Engine oil thermocouple

A Mod II DEC was populated, checked out, calibrated, and installed in the ASE test cell without incident.

Development plans were formulated for the design, development, and integration of an updated Stirling engine DEC. The scope of its applications was outlined and its preliminary functional requirements were defined.

#### MPC

Throughout this report period, primary emphasis was placed on the design of the MPC system and components for the Mod II engine, as well as testing prototypes of Mod II components on the Upgraded Mod I engine in the test cell.

MPC System Design - After several iterations and false starts, the basic design for the MPC was selected in order to take advantage of the engine characteristics during pump-down. In addition, a two-tank hydrogen storage system was chosen in order to avoid the necessity of using a two-stage compressor to achieve the low design idle pressure of the Mod II. In other aspects the Mod II design is functionally identical to the Mod I MPC system.

P(max) and P(tank) Control Blocks - The designs for the P(max) and P(tank) blocks were completed, the drawings were issued and the blocks were ordered. Although the P(max) block is functionally identical to the Upgraded Mod I model, it was extensively redesigned to make it more compact. It also utilizes a new pressure transducer to replace the troublesome Bell and Howell model used in the Mod I, as well as a much smaller, off-the-shelf relief valve to replace the custom manufactured USAB model. The P(tank) block

design uses two solenoid controlled valves for tank switching and a third solenoid valve for tank shut-off. An extensive search was conducted for a replacement for the solenoid valves manufactured by Valcor, but a suitable replacement was not found.

The P(tank) block uses the same transducers and relief valves as the P(max) block. The software to operate the two-tank system was written. A prototype two-tank hydrogen storage system was successfully tested in the test cell.

The hydrogen storage bottles selected for the Mod II were of Kevlar-wrapped aluminum construction resulting in substantial weight savings over the Mod I type steel bottle. One bottle was successfully fatigue tested to 10 million cycles.

Check Valves - The design for the Mod II valves was accelerated because of additional failures of the Mod I type check valves. The valves were redesigned to incorporate an O-ring seal and more shock and heat resistant materials were specified. The first of the new valves were delivered in December and plans were to install them in the USAB endurance engine and Spirit engines as soon as practicable.

PCV - The PCV was redesigned to replace the hydraulic servo with an electric motor-driven actuator which drives the sliding spool valve through a reduction gearbox and rack and pinion drive. In addition, a "stinger rod" type flexible linkage was incorporated to reduce actuator-to-spool alignment problems. The design and drawings were completed and ready to be issued in early January.

A prototype electrically-actuated Upgraded Mod I valve was successfully tested in the test cell. Its performance, under all operating conditions, was very good. It is, as expected, much faster than the Mod I electrohydraulic actuator. Figure 3-42 illustrates the actuator performance during a power increase engine transient. The most difficult condition

for actuator operation, however, is at a low engine speed idle. Figure 3-43 illustrates the very good idle control by the actuator. The idle conditions were 400 rpm and 30 bar P(max) pressure (2.5 MPa mean pressure). The actuator will be tested in the Spirit in January 1986.

Hydrogen Compressor - The initial design for the three-volume hydrogen compressor was completed at USAB. The design was extensively reworked at MTI, the drawings were completed and issued, and the pieces were ordered. The design consisted of two pistons mounted on the same rod, one atop the other, with the bottom piston being double acting. This yielded three pumping volumes which could be independently controlled by selectively bypassing outlet flow back to the inlet through three coaxially mounted electrically operated solenoid valves. The volumes can be combined to give different pumping rates. Of the seven possible combinations, the final design yielded five usable, progressively higher pumping rates. The decision was made to initiate parallel procurement of three compressors; two at USAB and one at MTI.

Two-Tank System - A prototype two-tank system was tested in the ASE engine cell. The system performed very well, providing good engine response. The hardware and software were evaluated and determined to be sufficiently reliable for installation in the Spirit Transient Test Bed (TTB), where the performance testing will be conducted.

Figures 3-44(a&b) and 3-45 show typical two-tank system pump-down and maximum power transients, respectively. Note that during pump-down, the compressor initially pumps to the high tank until maximum pressure (200 bar) is reached. The selector then switches to the low tank to complete pump-down. During supply initial supply is from the low tank until low tank and engine pressure cross over. Then supply is continued from the high tank.

## Mod II Electronics Development

Two prototypes of the dual-fuel injector PWM board were produced to support DAFC testing. Artwork for a printed circuit version of this board was completed and all materials have been ordered.

A prototype compressor-bypass driver board was also built and successfully tested. All material needed to produce a printed circuit version of this circuit is currently on order as well.

Auxiliares Development - Blower and Alternator Development - Design progress during this half year included completion of the Mod II blower motor design. Drawings were finalized for the blower motor, castings, and impeller. These were also sent out for manufacture. A prototype motor was rewound. Two Mod II alternators were procured.

Testing of the Mod II alternator and a prototype motor coupled to a Mod I blower was carried out both on the bench and in the test cell. Engine temperature was successfully controlled using this electrically-driven blower without an air throttle.

$\Delta$ PEHS analysis by USAB showed larger pressures than in the Mod I. Inlet pressure drop analysis was done at MTI, and blower design was based on the updated  $\Delta$ PEHS. Belt loss analysis was done and a comparison of Mod I variator blower drive versus electrically-driven Mod I blower was done. Cooling airflow requirements for the Mod II alternator were determined.

## Electronics Development for the Blower and Alternator

A prototype of the brushless DC blower drive circuit was built and subjected to extensive debugging. The testing process proved that hall effect sensors used to obtain commutation position from the rotor magnet would be noise prone. A shaft mounted strobe wheel and optical sensors were added to the motor to replace the

hall effect devices and performed flawlessly. Several different types of power transistors were tried before ones were found that could survive the electrical stresses at the higher blower speeds.

In the BSE test cell, the blower system proved that it could track demand very precisely and without significant overshoot. The preliminary tests on the bench showed a drive electronics efficiency on the order of 90%, very close to the prediction made at the August design review at NASA.

A computer simulation of the brushless DC blower system was written and provided valuable qualitative information in the areas of efficiency and optimum commutation angle. The initial commutation angles were set using this information.

The initial version of the PWM regulated battery charge system was prototyped and subjected to preliminary testing.

ORIGINAL PAGE IS  
OF POOR QUALITY

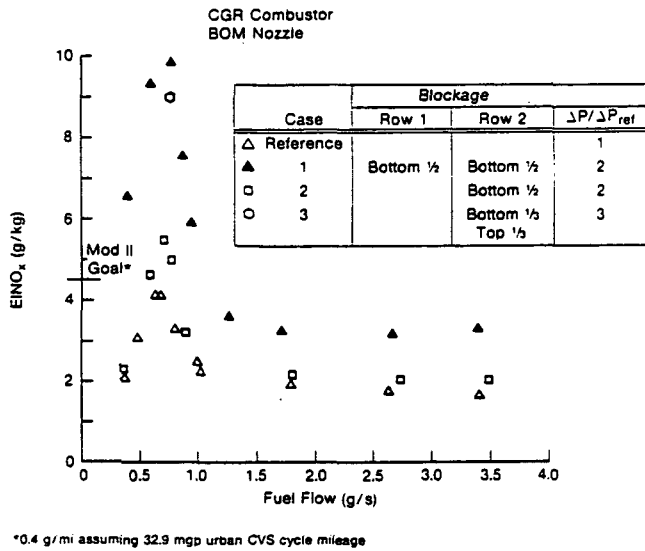


Fig. 3-1 Effect of Heater Head Blockage on Engine No. 3  $NO_x$  Emissions with Air Atomization at 720°C

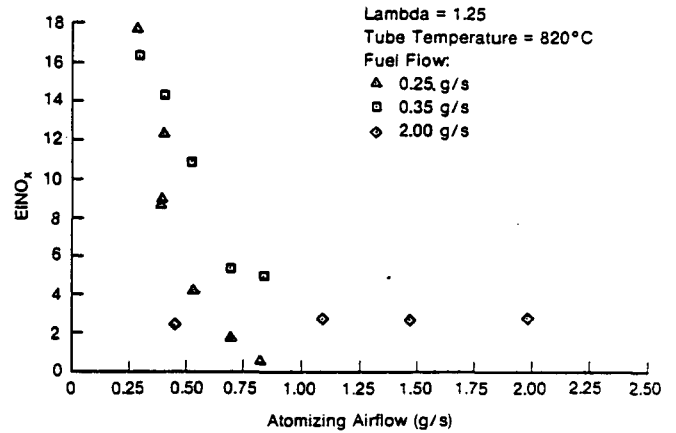


Fig. 3-3 Effect of Atomizing Airflow on  $NO_x$  Emissions

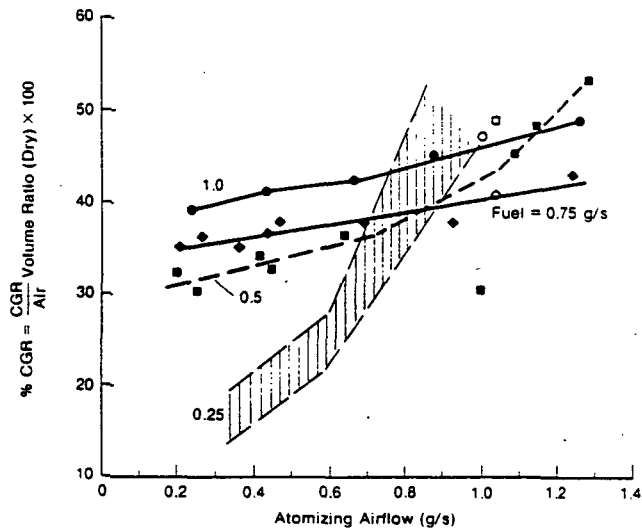


Fig. 3-2 Effect of Atomizing Air on Measured Performance Rig %CGR with the BOM Nozzle

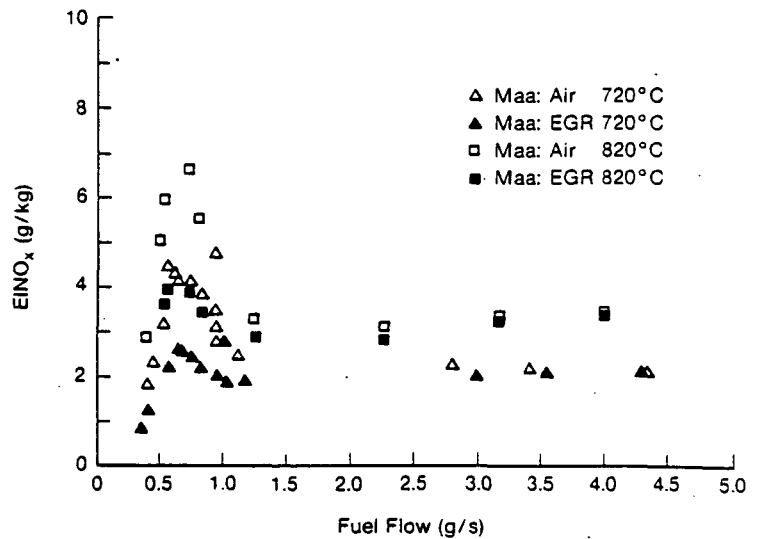
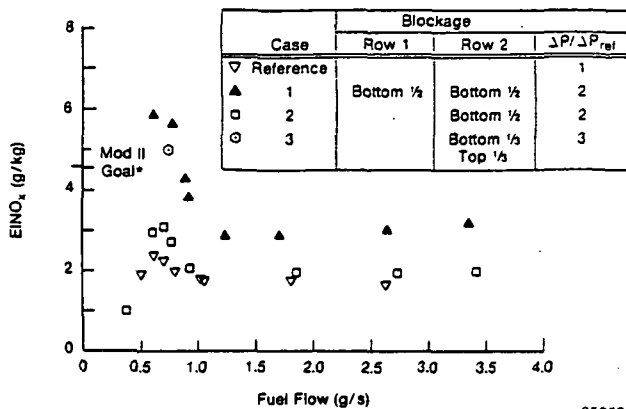
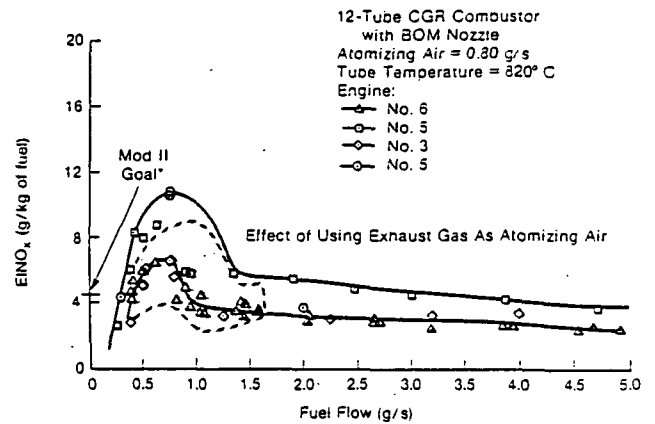


Fig. 3-4 Effect of Atomizing Fluid on Engine No. 3  $NO_x$  Emissions at Different Heater Head Set Temperatures



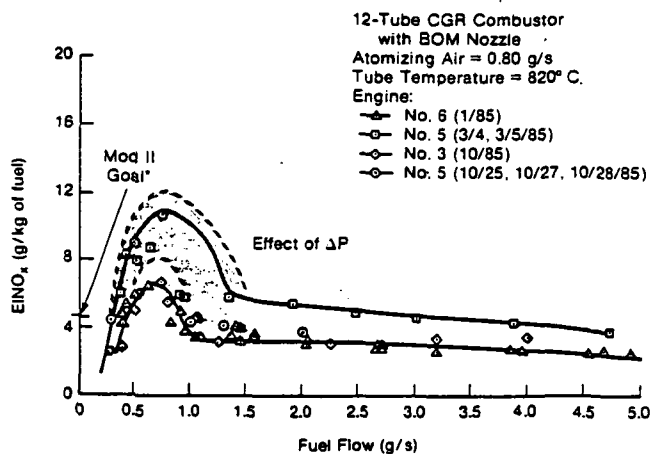
\*0.4 g/mi assuming 32.9 mpg urban CVS cycle mileage

Fig. 3-5 Effect of Heater Head Blockage on Engine No. 3  $NO_x$  Emissions with Exhaust Gas Atomization at 720°C



\*0.4 g/mi assuming 3.29 mpg urban CVS cycle mileage

Fig. 3-7 Effect of Exhaust Gas Atomization on  $NO_x$  Emissions



\*0.4 g/mi assuming 3.29 mpg urban CVS cycle mileage

Fig. 3-6 Effect of Mod II Heater Head  $\Delta P$  on  $NO_x$  Emissions

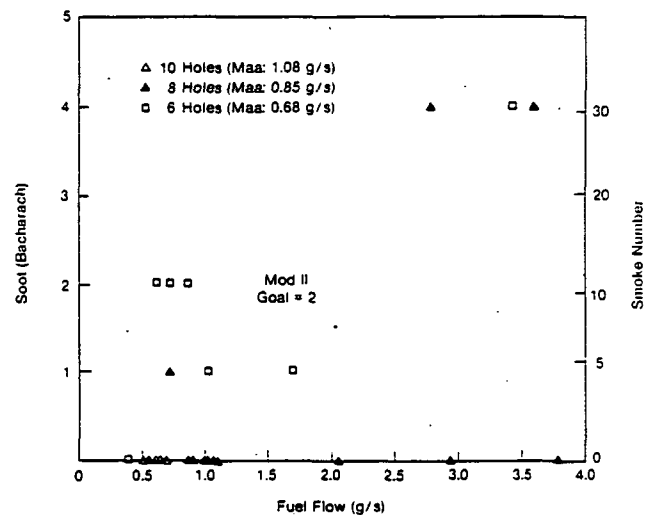
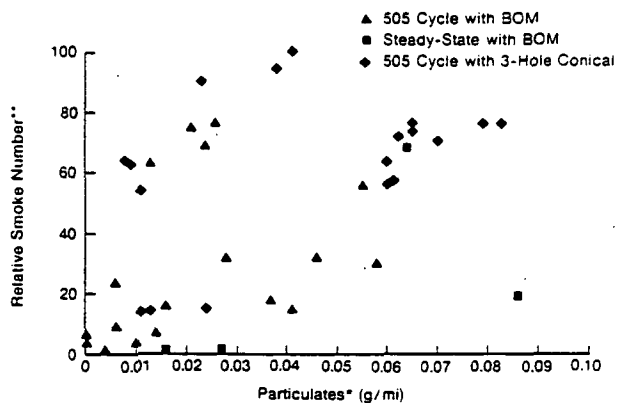


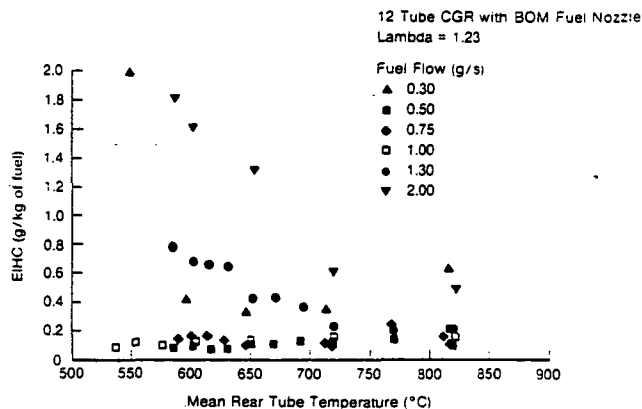
Fig. 3-8 Effect of Reduced BOM Nozzle Atomizing Airflow on Engine No. 3 Soot Emissions at 720°C



\*Mod II Goal = 0.2 g/mi (Urban CVS Cycle)

\*\*Transient Smoke Numbers Are Not Correlated to Steady-State Results Due to Higher Volumes of Sampled Exhaust Gas

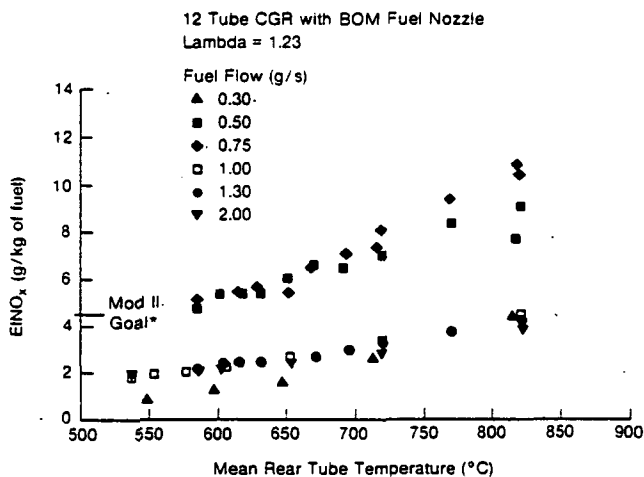
Fig. 3-9 Soot versus Particulates with the CGR Combustor - Spirit Vehicle



Test Days:

October 24, 25, 27 and 28, 1985

Fig. 3-11 Effect of Tube Temperature on Engine No. 5 HC Emissions



\*0.4 g/mi assuming 32.9 mpg Urban CVS Cycle Mileage

Figure 3-10 Effect of Tube Temperature on Engine No. 5 NO<sub>x</sub> Emissions

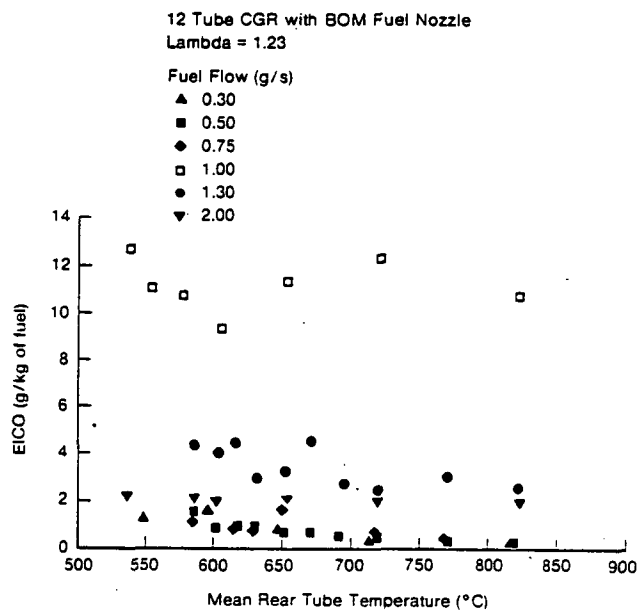


Fig. 3-12 Effect of Tube Temperature on Engine No. 5 CO Emissions

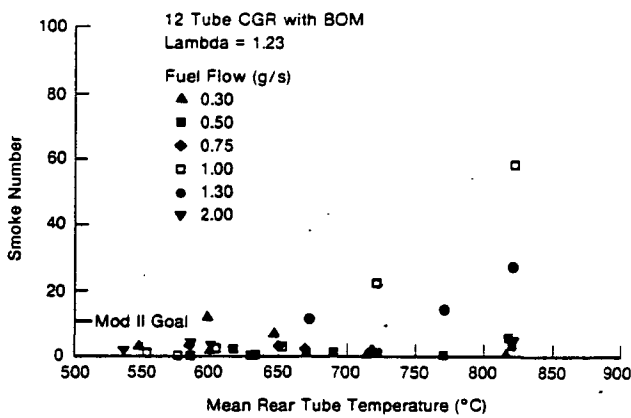
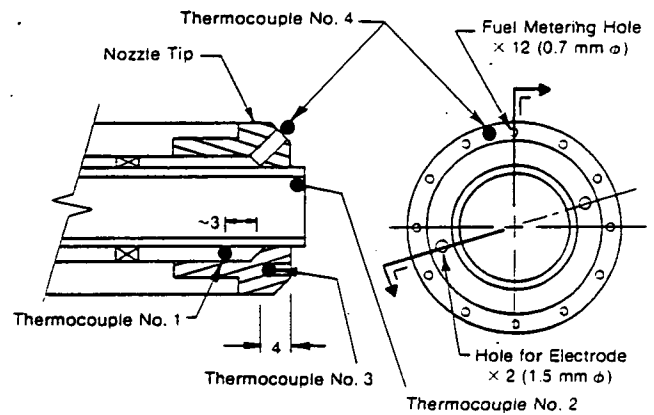


Fig. 3-13 Effect of Tube Temperature on  
Engine No. 5 Smoke Number



Thermo- couple No.	Description
1	Fuel/Air Mixture
2	Center Sleeve
3	Metal Temperature between Fuel Holes (Shielded)
4	Metal Temperature — Pressed into Electrode Hole

Fig. 3-15 BOM Nozzle Thermocouple Locations

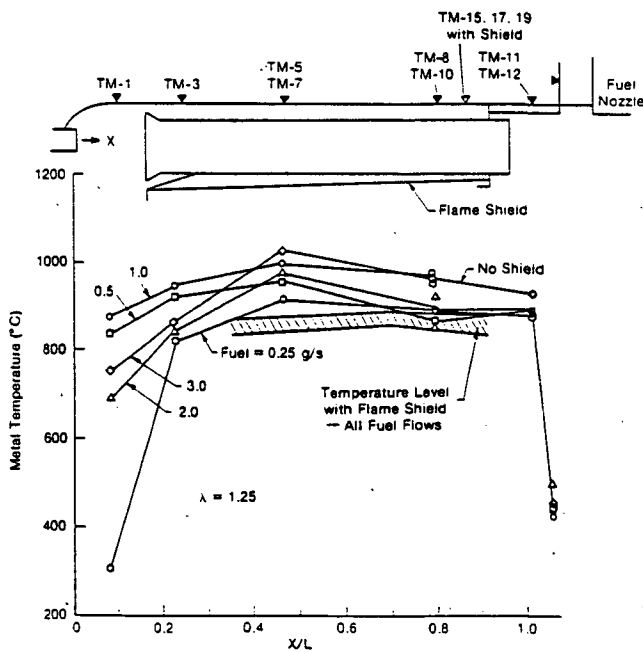


Fig. 3-14 Variation of CGR Combustor Shell  
Temperature Along the Mixing Tube Centerline

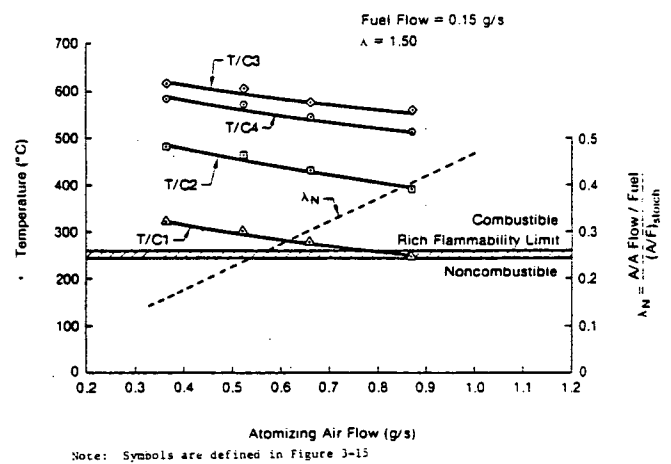


Fig. 3-16 Effect of Atomizing Airflow on Nozzle  
Temperature (Mod I 12-Tube CGR Combustor  
with BOM Nozzle)



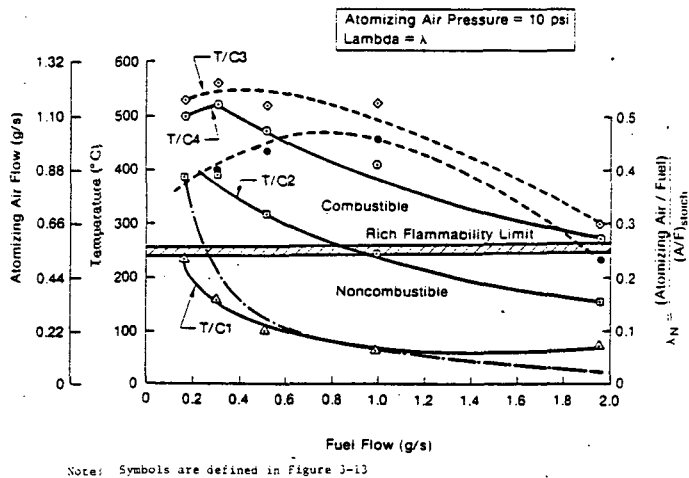


Fig. 3-17 Effect of Fuel Flow on Nozzle Temperature (Mod I 12-Tube CGR Combustor with BOM Nozzle)

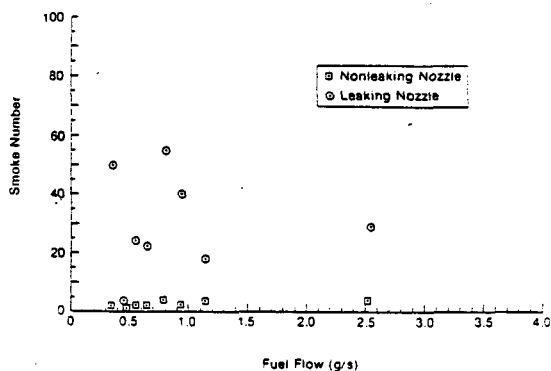


Fig. 3-18 Effect of BOM Nozzle Leakage on Soot Emissions at 720°C

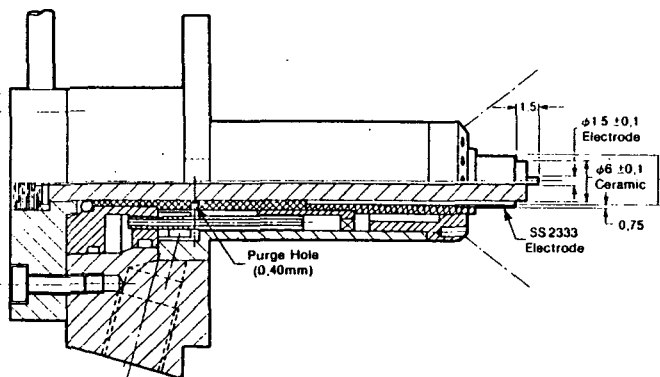


Fig. 3-19 Modified BOM Nozzle with Concentric Center Electrode

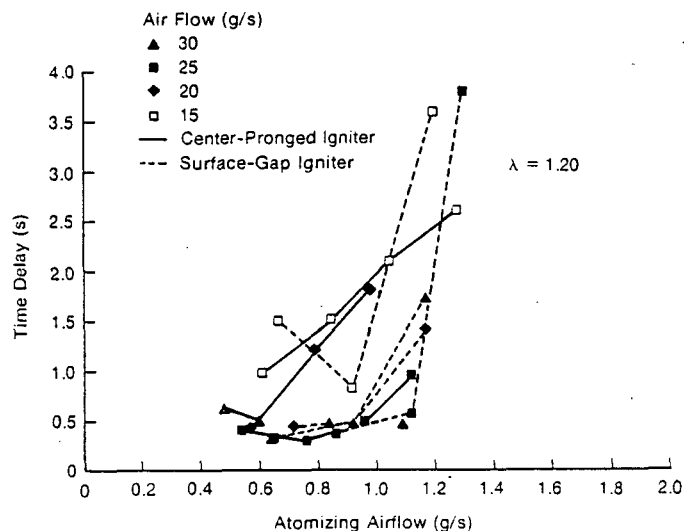


Fig. 3-20 Effect of BOM Igniter on CGR Ignition Delay

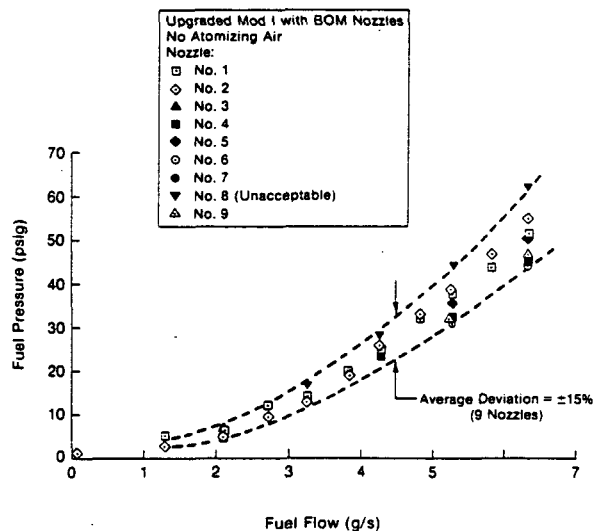


Fig. 3-21 Standard Upgraded Mod I BOM Nozzle Cold Flow Calibration

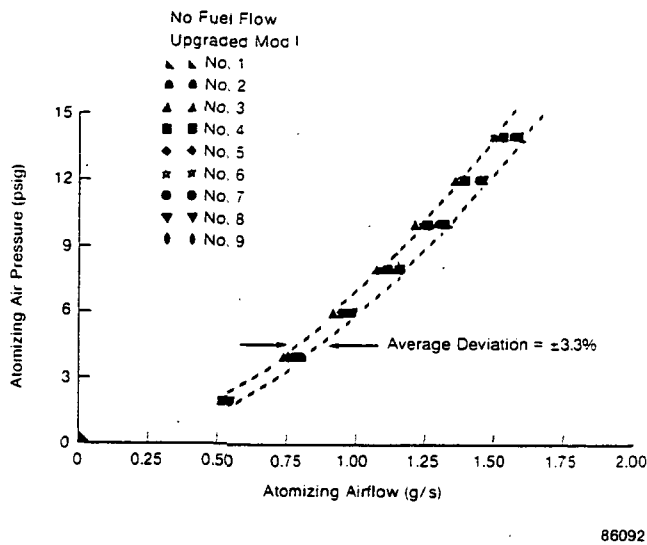
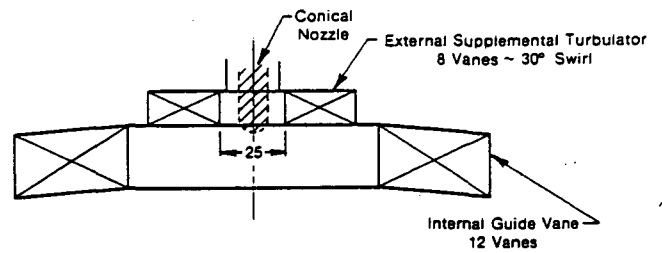
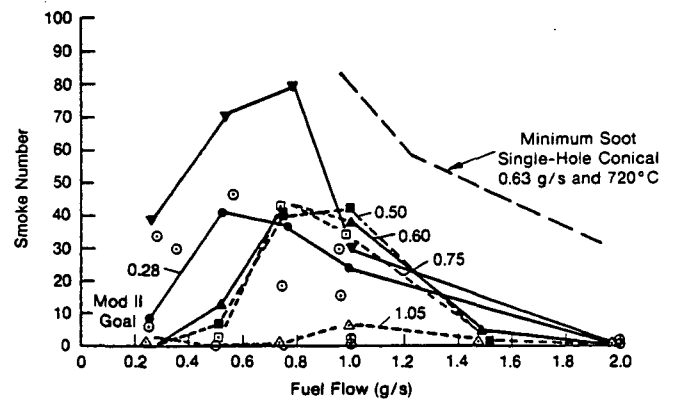
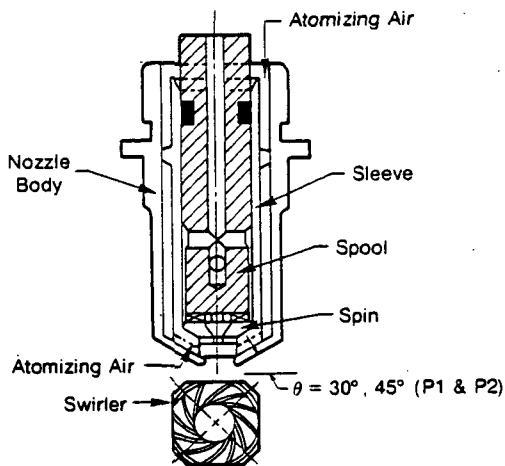


Fig. 3-22 Standard Upgraded Mod I BOM Nozzle  
Cold Flow Calibration



Swirl Angle (°)	ID (mm)
30	25
30	35
45	25
45	35

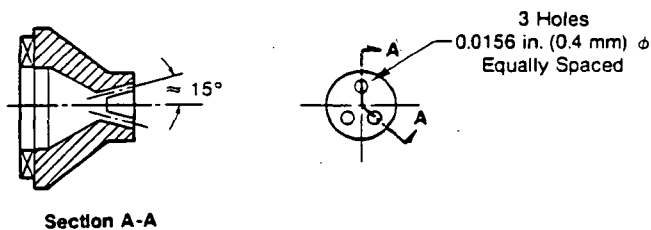
Fig. 3-24 CGR Combustor Modifications



853582

Nozzle	Atomizing Airflow (g/s)
○ BOM	0.6-1.1
▼ 3-Hole Conical	0.18
● 3-Hole Conical	0.28
■ 3-Hole Conical	0.50
▲ 3-Hole Conical	0.60
□ 3-Hole Conical	0.75
△ 3-Hole Conical	1.05

Fig. 3-25 Comparison of Soot Emissions with  
CGR Burning Gasoline



Original Spin Chamber: 1 Hole 0.032 in. (0.81 mm)  $\phi$   
Area Ratio: New/Old = 0.71

Fig. 3-23 Increased Momentum Fuel Spin  
Chamber Conical Nozzle

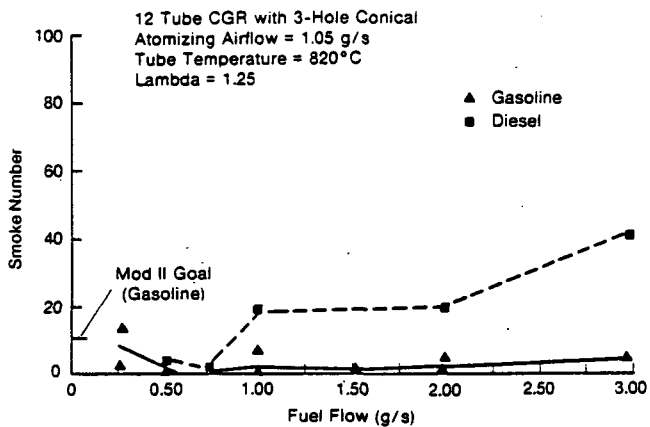


Fig. 3-26 Effect of Fuel on Smoke Number

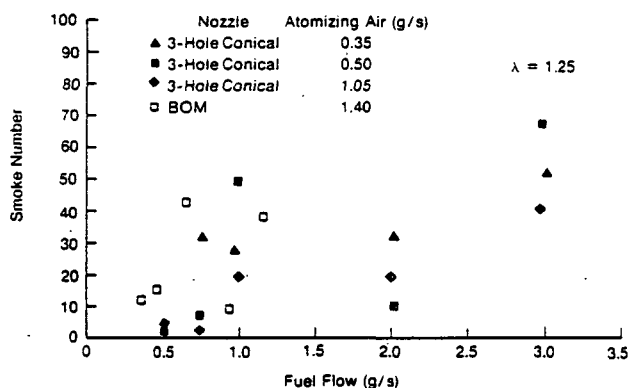


Fig. 3-27 Effect of Fuel Nozzle and Atomizing Airflow on Diesel Fuel Soot Emission with a CGR Combustor

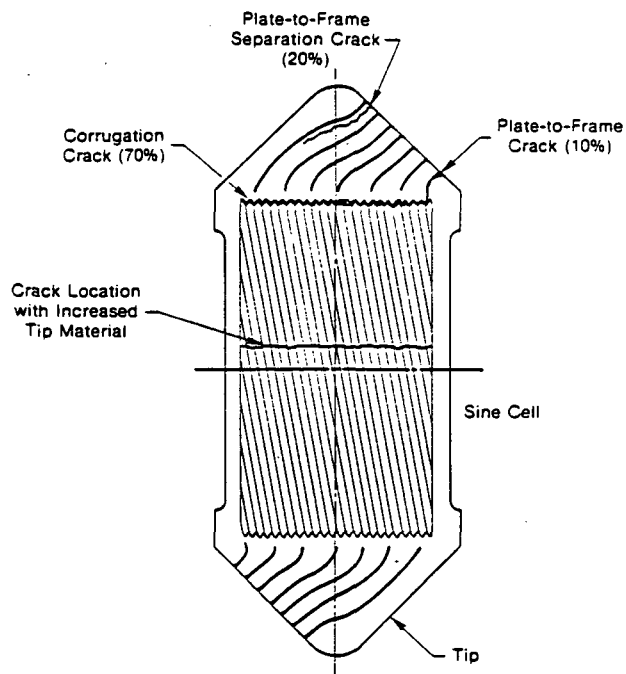
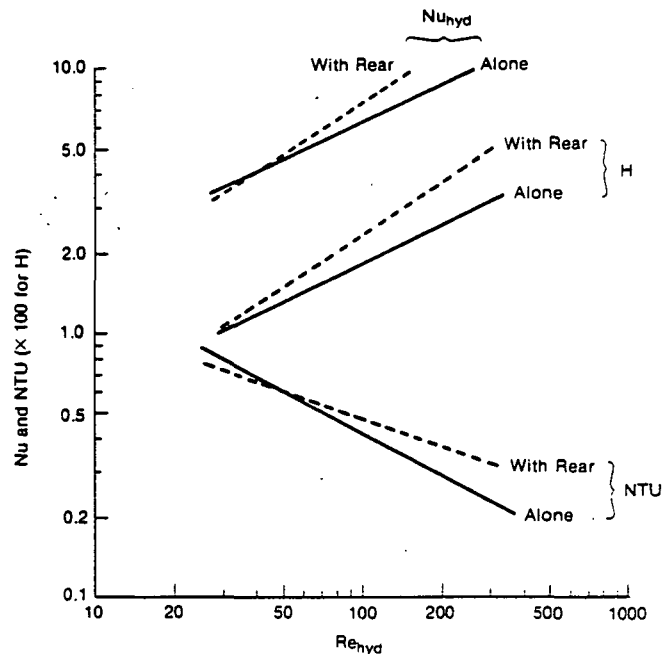
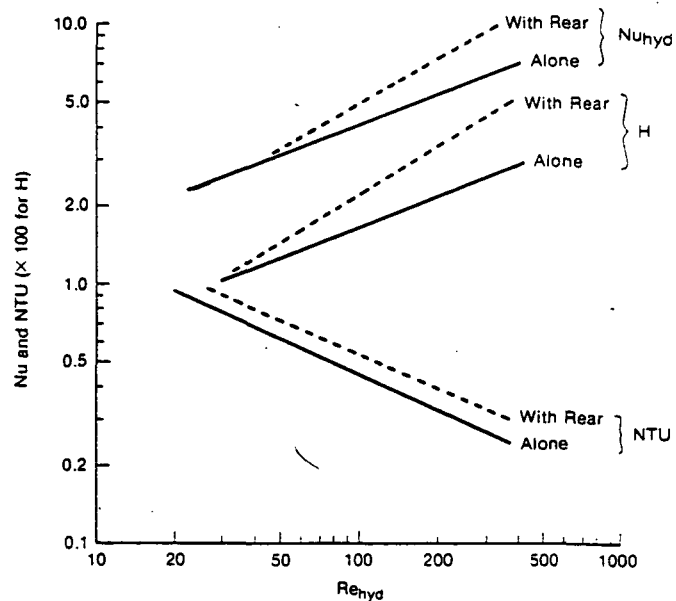


Fig. 3-28 Ceramic Preheater Plate Cracks



Note: Rear Test Section was Mod II (-0218)  
Tests with Rear Section were at 800°C Tube Temperature, Lambda  $\approx$  1.35  
Tests without Rear Section were at 500°C Tube Temperature, Lambda  $\approx$  1.70

Fig. 3-29 Comparison of NTU, Nu, and H with Front Test Section -0217 when Run with and without Rear Test Section, Least Squares Fit of Data (6/85-8/85)



Note: Rear Test Section was Mod II (-0218)  
Tests with Rear Section were at 800°C Tube Temperature, Lambda  $\approx$  1.35  
Tests without Rear Section were at 500°C Tube Temperature, Lambda  $\approx$  1.70

Fig. 3-30 Comparison of NTU, Nu, and H for Front Test Section -0301 when Run with and without Rear Test Section, Least Squares Fit of Data (6/85-8/85)

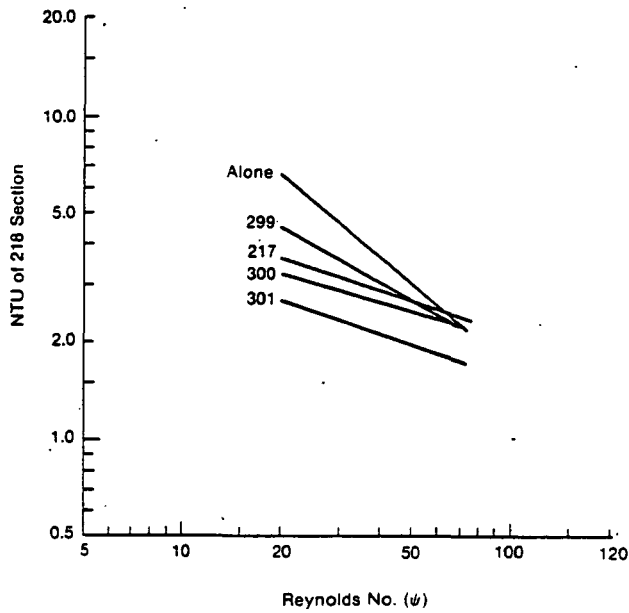


Fig. 3-31 Comparison of Rear Row Performance (218) for Various Front Row Geometries and Alone

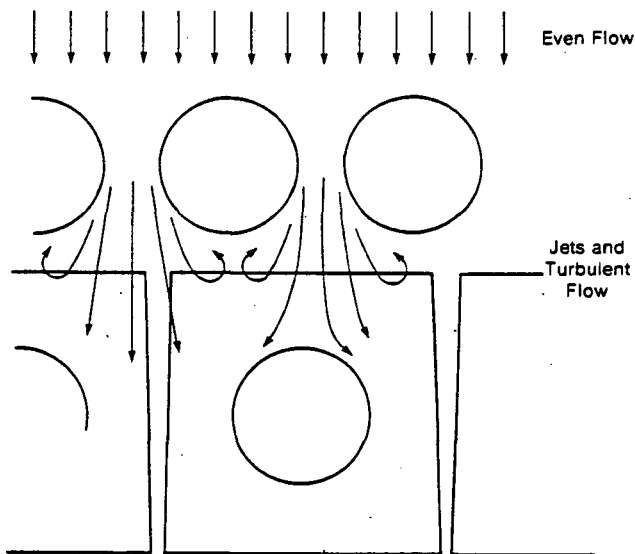


Fig. 3-32 Front Row Effect on Rear Row

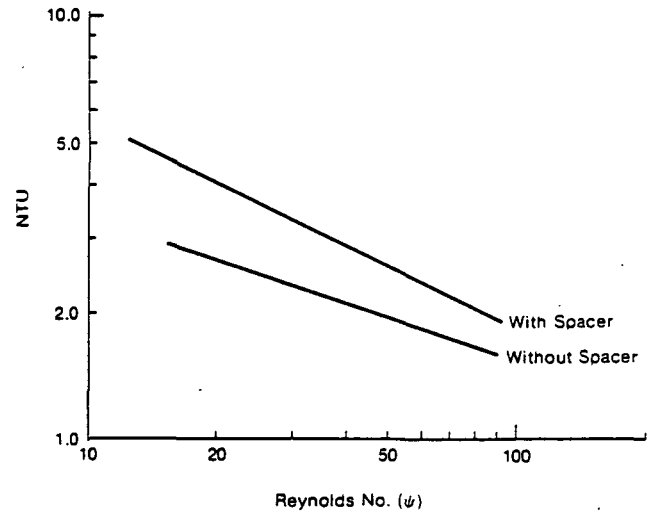
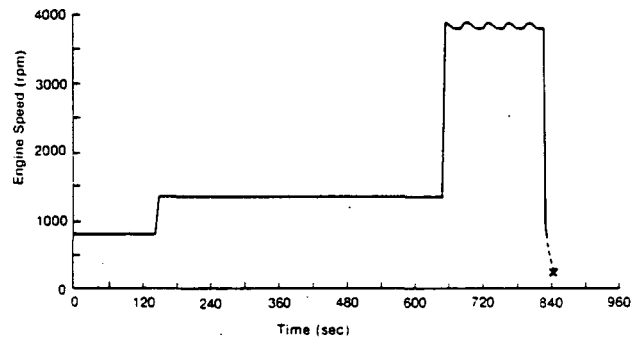
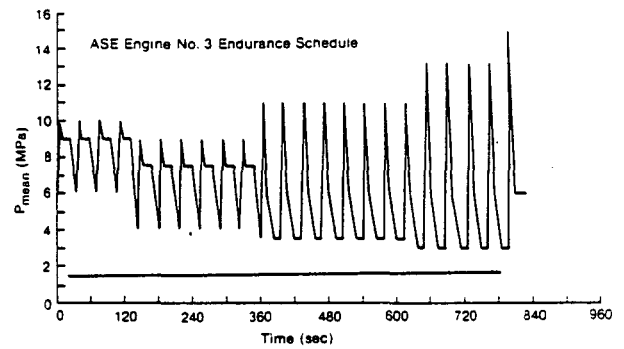


Fig. 3-33 Ntu versus Re - 218 Run Together with 301 and without 20 mm Spacer



ASE Engine No. 3 Endurance Cycle

85721

Fig. 3-34 CVS Endurance Cycle for Engines No. 6 and 7

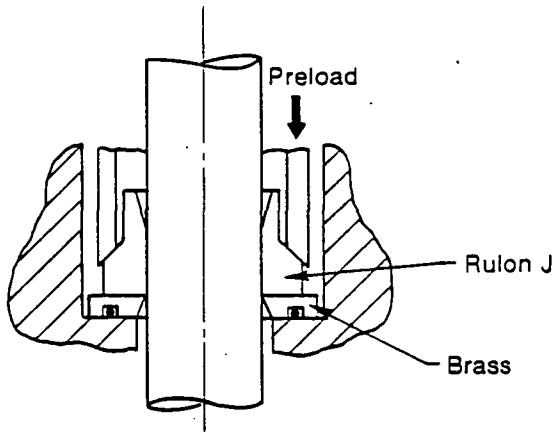


Fig. 3-35 Compound Main Seal

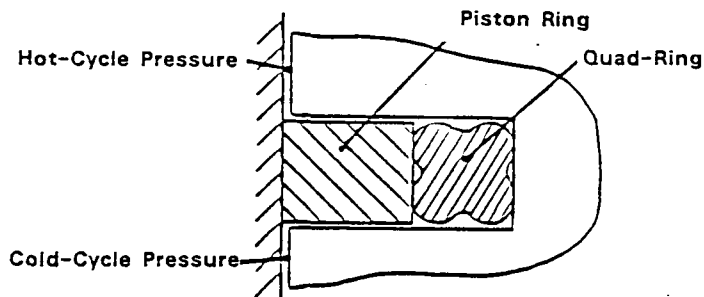


Fig. 3-36 Single-Solid Piston Ring

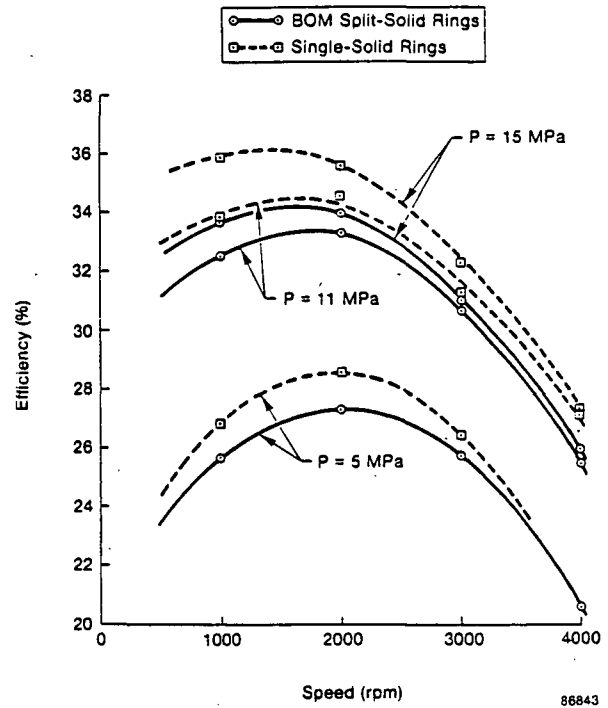


Fig. 3-37 Piston Ring Performance, Engine No. 5

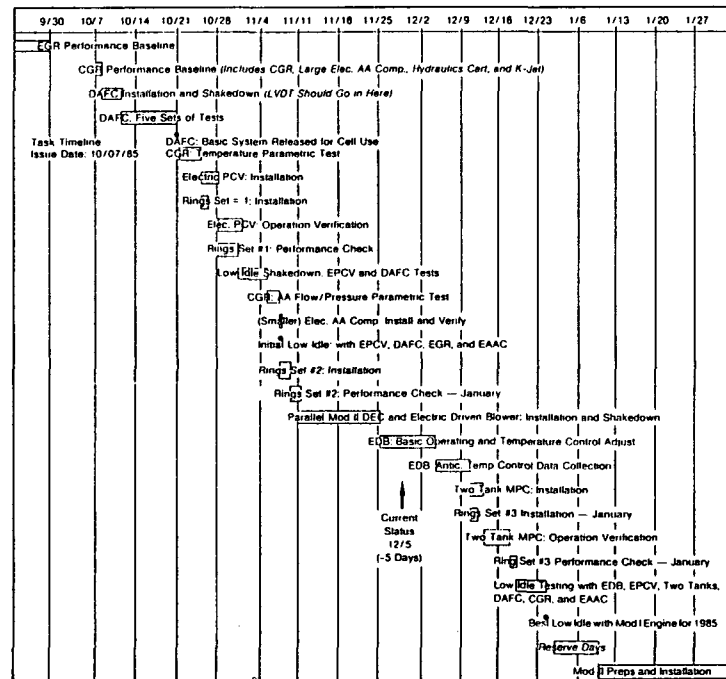


Fig. 3-38 Controls, Auxiliaries, and Components  
Development in Engine Cell

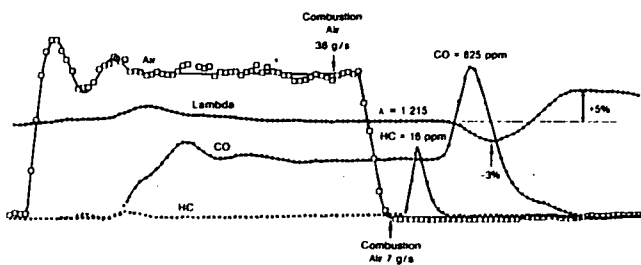


Fig. 3-39 Transient Tests on DAFC (1 data scan/sec)

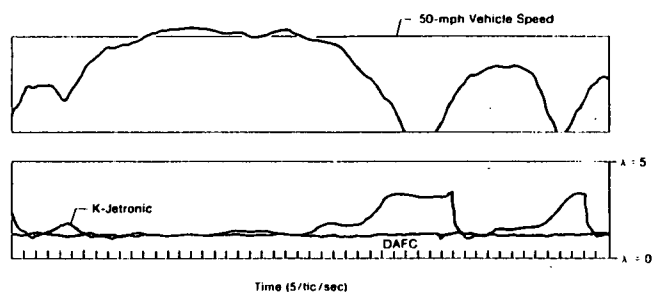


Fig. 3-40 Urban  $\lambda$  Response: K-Jetronic and DAFC

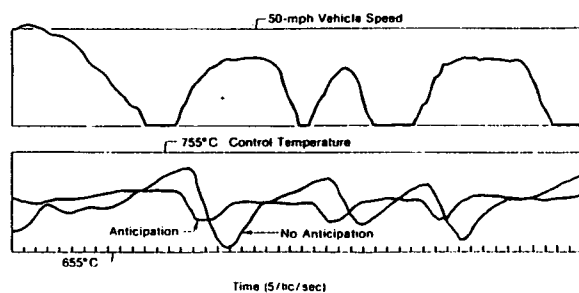


Fig. 3-41 Temperature Control with and without Anticipation

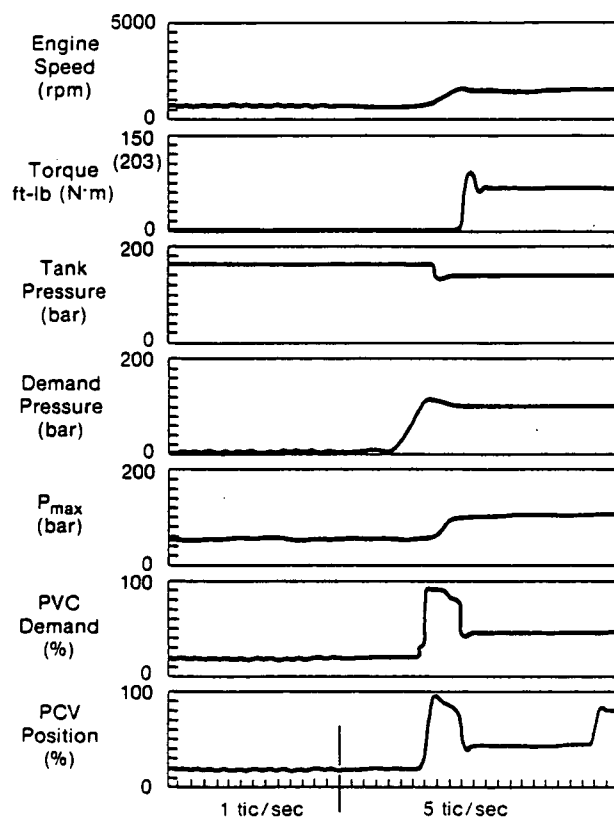


Fig. 3-42 Electric Actuator Performance - Up-Power Transient from Idle (750 rpm, 52 bar)

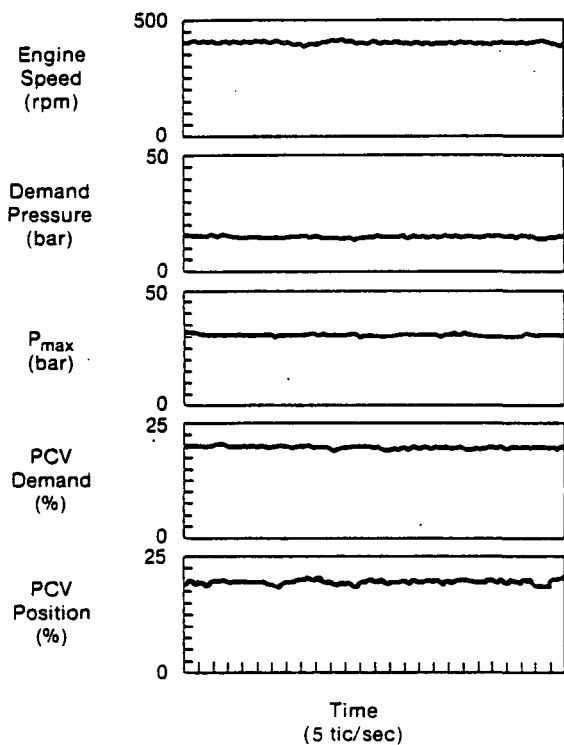


Fig. 3-43 Electric Actuator Performance - Low Pressure (30 bar  $P_{max}$ ), Low Speed (400 rpm) Idle

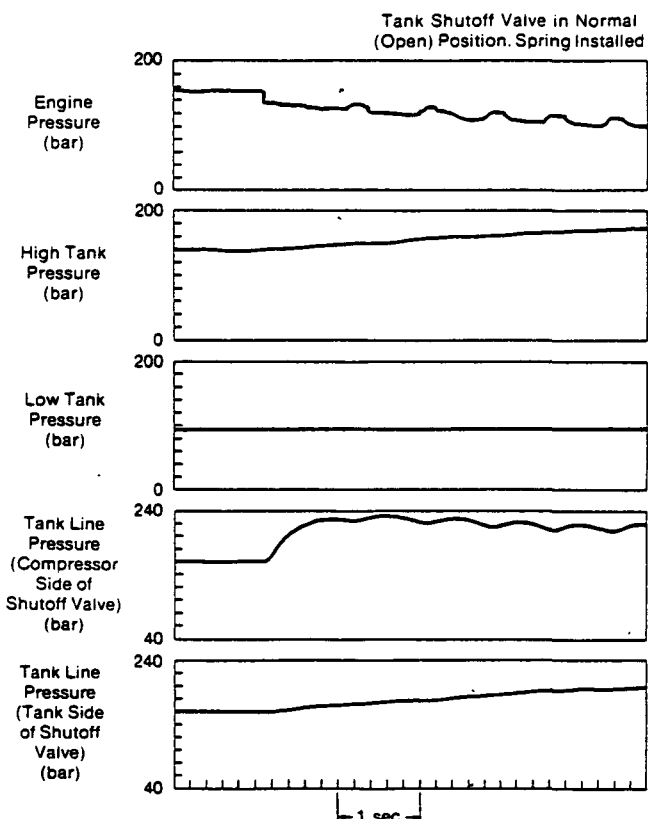


Fig. 3-44a Typical Two-Tank System Pump-Down

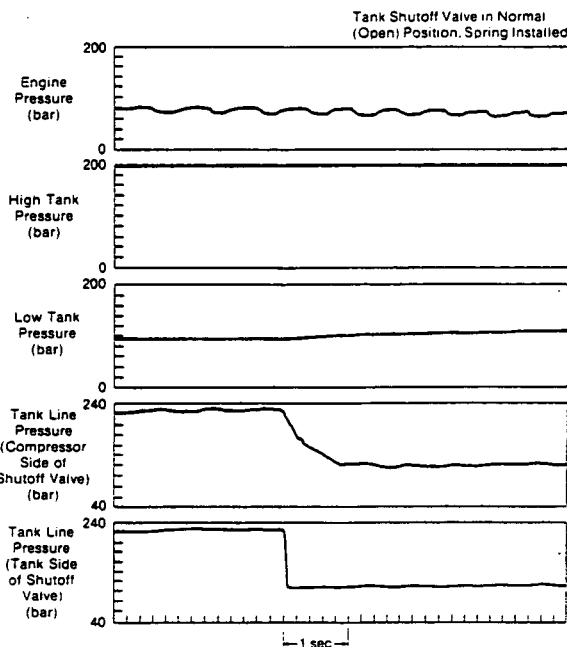


Fig. 3-44b Typical Two-Tank System Pump-Down (Cont'd)

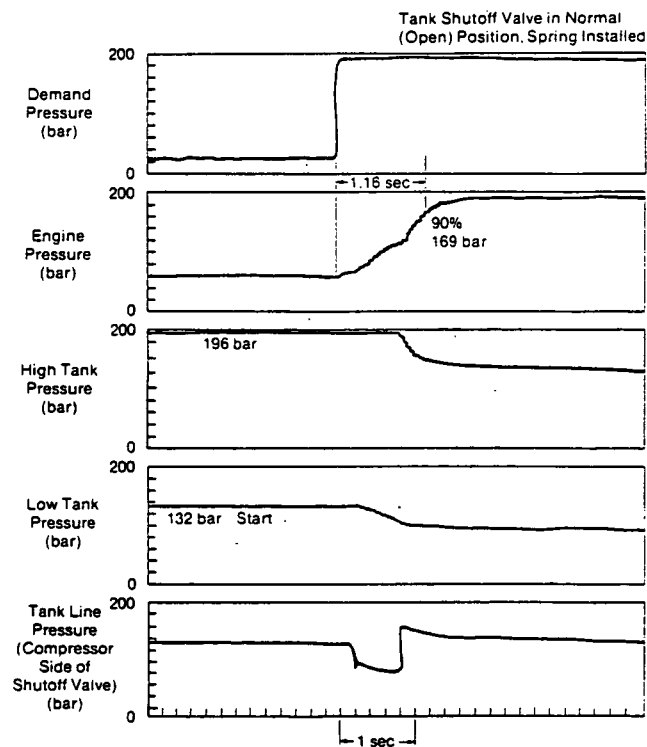


Fig. 3-45 Two-Tank System Maximum Power Transient Test

## IV. MOD I ENGINE DEVELOPMENT

### Mod I Hardware Development

During the last half of 1985 the Mod I engines still in the ASE Program were devoted to the development of technologies related strictly to the Mod II engine program. With this in mind the development of the Mod I engines were curtailed if it was not directly applicable to the Mod II engine program. The major efforts therefore on the Mod I program were as follows:

- CGR combustors
- Single-solid piston ring evaluations
- Cold starts
- Fuel nozzle evaluations
- Mod II controls and auxiliaries prototype evaluations
  - DAFC
  - Electric PCV
  - Electric blower
  - High voltage alternator
  - Two-tank system
  - Mod II DEC

### Mod I Hardware Follow-Up Report

The following is a report on Mod I hardware development which updates an earlier report given in SA8.

#### Mod I High Temperature Heater Heads

The "high temperature" heater heads are still in operation on all of the Mod I engines including the 820°C endurance test engine at USAB. To date, the high time quadrant is on this endurance engine and has accumulated over 2500 hrs of operation at the elevated temperatures. The other three quadrants on this engine have close to 2000 hrs of operation. Testing will continue until a total of 3500 hrs (their design life) have been attained.

These quadrants feature the two heater head development materials of CG-27 tubes and XF-818 castings.

#### Crankcase Bedplate Cracking

Since the new design was put into service no cracks have been found in service. Over 2500 hrs have been obtained on one casting of this design. No future reports will be given on this subject unless it develops some problems.

#### Heater Tube Failures

During this report period no tube failures had occurred.

#### Cylinder Liner Top O-ring Deterioration

Testing conducted on the 820°C endurance engine at USAB has been evaluating the removal of the lower water seal O-ring from the top of the cylinder liner. This configuration was described in SA8. The configuration while providing longer overall upper gas seal O-ring life does not, in the Mod I design, offer a cure which will allow the O-ring to last for the desired 3500 hrs of operation. The configuration does appear to allow 1000 hrs of O-ring operation at 820°C. The Mod II design will require lower temperatures in this area for its Viton O-rings to last. The annular configuration should help lower the O-ring area temperature.

#### Hydrogen Compressor Small End Bearing Bushings

At this time no new solution has been found for the deterioration of the small end bushings on the compressor connecting rod. One discovery was that the valve the compressor was pumping against was much more restrictive than originally thought, which during pump-downs possi-



bly could result in overloading the compressor. The valves have been eliminated on some engines to evaluate the effects on compressor small end bushing life.

### **Mod I Engine Test Program**

In the last half of 1985 a total of six Mod I engines were operational at one time or another. Two of the engines are their original Mod I configuration and are located at USAB in Sweden. The remaining engines are Upgraded Mod I engines of which three are located in the United States at MTI and one at USAB. One of the Upgraded Mod I engines at MTI is assigned to a Army Generator set program, but was used during the period to obtain cold start data for a few weeks. The specific purpose of each engine is listed below:

- Mod I engine No. 3 (USAB) - EHS
- Mod I engine No. 7 (USAB) - Seals/Piston Ring Development
- Upgraded Mod I engine No. 5 (MTI) - General Development
- Upgraded Mod I Engine No. 6 (USAB) - 820°C Endurance Test
- Upgraded Mod I engine No. 8 (MTI) - Spirit Vehicle Engine
- Upgraded Mod I engine No. 9 (MTI) - Part Time Program Use, Generator Set

The following is an itemized account of the activities of the program engines. During the period an additional 2827 hrs were accumulated bringing the program total engine hours to 14,239. Figures 4-1 and 4-2 show an engine-by-engine plot of the total hours.

#### Mod I Engine No. 3

Mod I engine No. 3 accumulated a total of 153.0 hrs during the last half of 1985 bringing its total hours to 2023.1. During the period its prime assignment was EHS development. As a part of this task it was assigned to the component develop-

ment area to develop the CGR combustor, fuel nozzles, and atomizing air systems.

The specific results of this engines test programs are included under "Component Development" in Section III of this report. In CY 1986 this engine will be removed from actual operational use and will be used as a test bed for static seals development under cold ambient conditions. The EHS activities will be combined with engine No. 7 test program which will include seals development.

#### Upgraded Mod I Engine No. 5

Engine No. 5 at MTI accumulated a total of 171.0 hrs of operation during the last half of 1985 bringing its total operational hours to 1535.0. During this period it was idle for a period of three months. During the final three months of the year it was operated to evaluate prototype Mod II controls and auxiliaries hardware.

The details of the testing are covered under "Controls and Auxiliaries Development" in Section III of this report. Nearly all of the items performed well during operation and little or no problems were encountered. The electric blower was, however, the most problematic with transistors being blown in its control circuitry during accelerations of the engine. This problem was not resolved at the end of the year. Development of this particular component will have to be done on the vehicle since engine No. 5 was removed from test in the first week of 1986 to make room for the scheduled Mod II BSE run at the end of January 1986.

The engine will be rebuilt during the early part of the year and will be used as the engine for an Air Force Flight Line Van which is a part of a NASA Technology Utilization Program scheduled to begin in early 1986.

---

\*Figures can be found at the end of this section beginning on page 4-5.

#### Upgraded Mod I Engine No. 6

Engine No. 6 accumulated a total of 1134.5 hrs during the last half of 1985 bringing its total operating time to 2710.6 hrs. During the period, the engine reached a major milestone of completing 2000 hrs of operation at 820°C temperature levels. The engines performance at the 2000 hrs point was found to be at the same level as that at the beginning of the test program. The only major items replaced during the period were the cylinder liner O-ring mentioned earlier, the engines combustors, flame-stone, and one main seal which was replaced when oil was detected in one of the cycles.

The engine has been used to gather information on CGR combustor durability. The primary problem with the combustors has been cracking which has required removal and weld repairs.

The test cycle, which simulates a vehicular mileage accumulation cycle, will be modified to include some idle operation. Approximately 180 sec worth of idling will be added to the beginning of each cycle. The engine will operate with the new cycle until 3500 hrs have been accumulated on endurance.

#### Mod I Engine No. 7

Engine No. 7 accumulated a total of 1076.5 hrs during the last half of 1985 bringing its total operating time to 4480.0 hrs. During this period the engine was used primarily by the Component Development Seals Group to evaluate engine main rod seals and piston ring seals. The details of this testing will be covered in detail in Section III of this report. The primary seals evaluated during this period were a shorter version of the Mod I main seal, single-solid piston rings, and pumping-ring main seals.

#### Upgraded Mod I Engine No. 8

Engine No. 8 at MTI is located in the Spirit vehicle. During the last half of

1985, the engine accumulated a total of 159.0 hrs bringing its total operational hours to 1112.5. During this period the engine was assigned to be used for component development transient testing of prototype Mod II hardware. Evaluated during this time were the following Mod II component prototypes.

- DAFC
- Electric-actuated PCV
- CGR combustors
- Atomizing air systems
- Mod II candidate fuel nozzles.

The details of the individual tests conducted over-the-road and on chassis dynamometers was covered in Section III of this report. Testing will continue into next year and will taper off as the Mod II Celebrity vehicle activity picks up.

#### Upgraded Mod I Engine No. 9

During this report period the use of Engine No. 9 was limited to rebuild, performance testing and cold ambient start tests, as installed in a generator set. During the last half of the year the engine accumulated a total of 81.2 hrs. This brings the engines total operating hours to 333.9.

The engine was rebuilt and tested in the engine test cell at MTI. The performance of the engine is plotted in Figures 4-3 through 4-5.

Following the performance tests, the engine was installed in an Army supplied generator set. The set was checked out to 25 kW and delivered to the Army at Fort Belvoir, Virginia in December 1985. Prior to being turned over to the Army for evaluation, the set was installed in a cold chamber at Fort Belvoir and its cold ambient start capabilities were checked out. The engine was found to be startable down to 30°F. No serious gas leakage was noted. The main problem with starting below these temperatures was actual ignition and not the engines control electronics or hydraulics. It is expected that controls adjustments in the

A/F system may improve the engines starting capability which up to now had not ever been evaluated at cold ambients without problems from the other systems. The Army is expected to performance test the engine followed by a short endurance test.

### Mod I/Upgraded Mod I Analysis

ASE engine No. 9 was mated to an electrical power generator to be supplied to the U.S. Army for evaluation. Analysis was conducted to assess engine health, generator set installation effects, and maximum electrical power rating. To ensure that engine health was acceptable, a series of three tests were conducted to provide a step-by-step evaluation of the installation effects.

The first test series was conducted to assess basic engine health following an engine rebuild. To accomplish this, the engine was tested in a configuration identical to its original final acceptance test (full Stirling engine system except for engine-driven atomizing air compressor). Results of the test are shown on Figure 4-6, compared to original final acceptance data. Note that power and efficiency obtained are equal to or better than original final acceptance levels.

To provide a balance of high engine power output and long seal life, engine operating conditions of 2750 rpm and maximum allowable mean pressure of 12 MPa were selected. To mate to an 1800 rpm generator, a speed reducing gear set was installed on the engine. A second set of data was recorded with the speed reducer installed (Figure 4-7). The gear set efficiency using this data is calculated to be 92.2%, a reasonable level for a double gear set running in 90 W oil. Low efficiency would have indicated either gear set or engine health problems.

The final engine data was recorded with the full generator installation (Figure

4-8). Lowest allowable engine P(max) is 80 bar to ensure adequate engine response, and power reduction below that pressure level is achieved by increasing the amount of engine short circuiting. A typical range of diesel-powered generator set efficiencies is shown in the figure. Note that the Stirling generator set efficiency levels are expected to be comparable to the diesels, even though the Stirling engine has not been optimized for this application. An assessment of engine health was made by back calculating generator efficiency after adjusting performance to the installed configuration (Table 4-1). The value thus obtained (79%) is reasonable, since generators of this size are typically 80%. This indicates (by deduction) that the engine was healthy at the completion of its installation. The measured power level at rated engine pressure of 12 MPa P(mean) 140 bar P(max) was 23.3 kW. A maximum rating of 20 kW was selected to allow deterioration margin. The engine was then released to the U.S. Army.

TABLE 4-1

#### FINAL GENERATOR SET PERFORMANCE 185 bar P(max), 720°C Set Temperature

Power Level (kW)	Comment
43.3	Measured on dyno stand with gear reduction unit. No AAC, generator set, or fan. Cooling water temperature = 50 C
-1.7	Estimated power reduction for atomizer air compressor engine driven
-3.0	Estimated power reduction for cooling fan
-2.0	Estimated power reduction for cooling water temperature = 80°C
37.6	Estimated net power input to generator
29.7	Measured electric power output
	Calculated generator efficiency = 29.7/37.6 = 79.9%

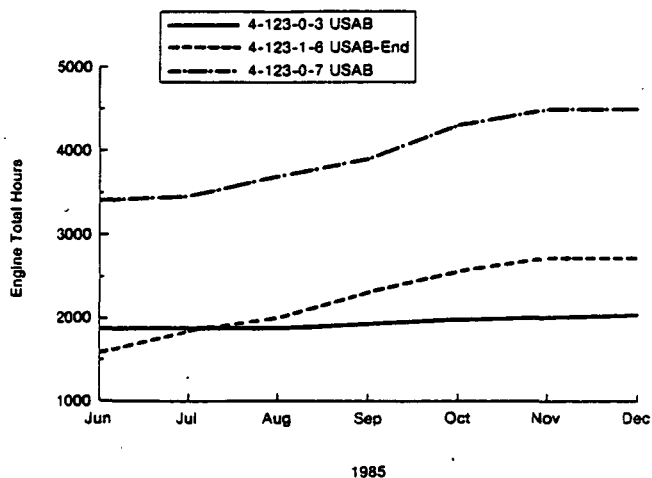


Fig. 4-1 Engine Operating Hours at USAB

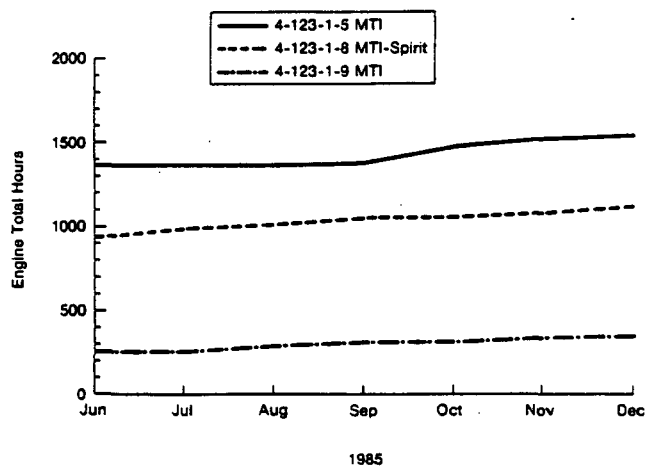


Fig. 4-2 Engine Operating Hours at MTI

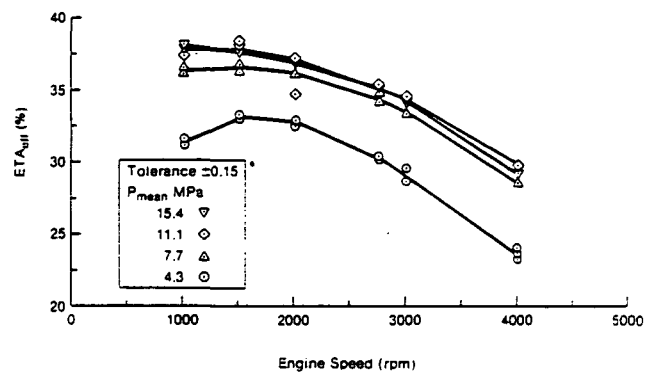


Fig. 4-3 Engine No. 9 System Efficiency Prepared for Genset Installation

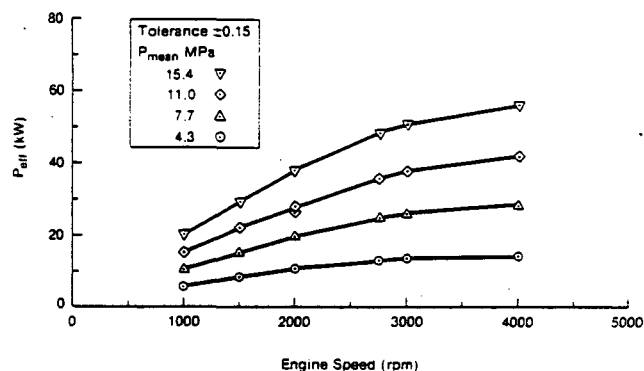


Fig. 4-4 Engine No. 9 Net Power as Prepared for Genset Installation

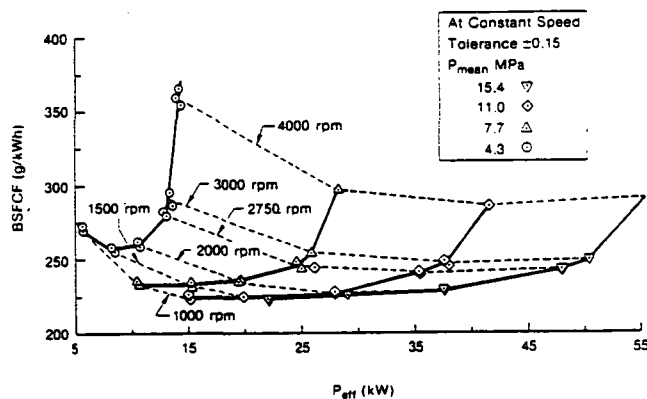


Fig. 4-5 Engine No. 9 BSFC as Prepared for Genset Installation

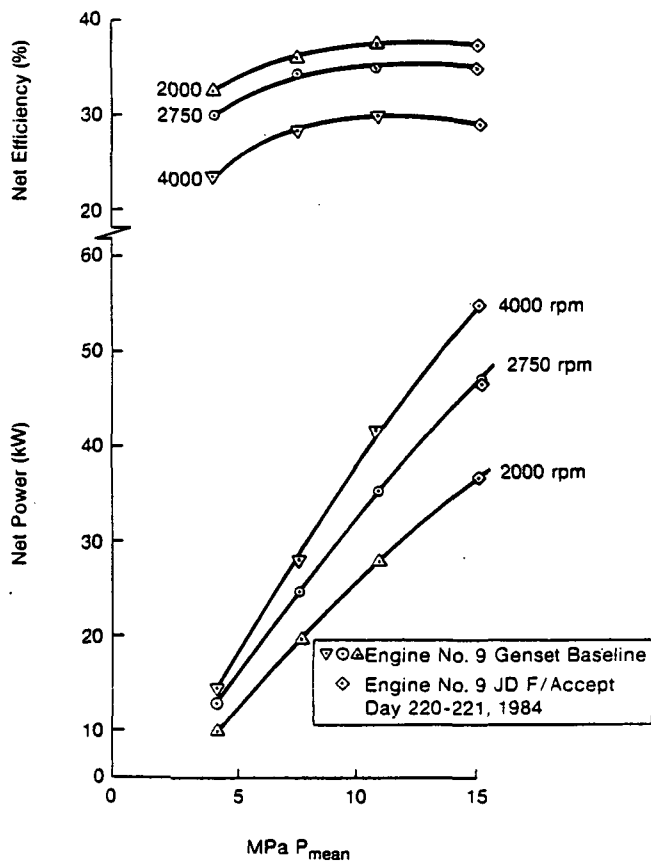


Fig. 4-6 Engine No. 9 Baseline Performance

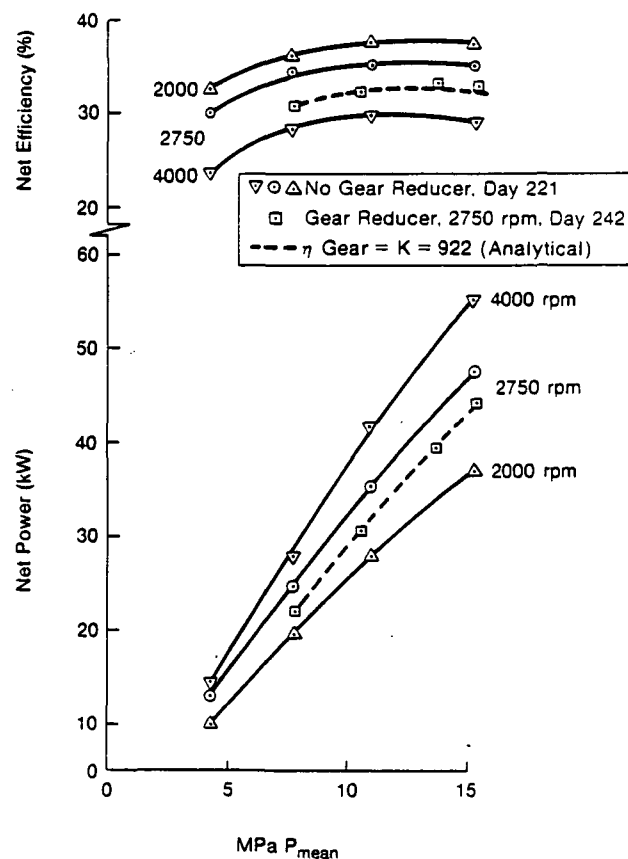


Fig. 4-7 Engine No. 9 Performance with Gear Reducer

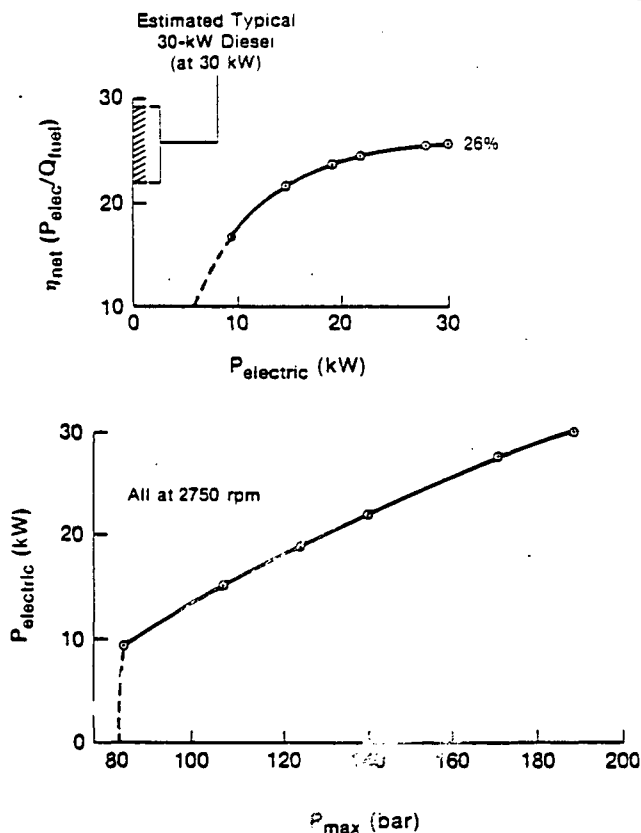


Fig. 4-8 Engine No. 9 Genset Performance

## V. MOD II PRELIMINARY DESIGN

### Introduction

The initial design of the Mod II BSE and several aspects of the SES controls and auxiliaries were completed during the first half of 1985, and reported in SA8. During this report period, three major design activities were accomplished:

1. A continuing series of engineering changes to drawings of BSE components was processed
2. Design and drawings for the engine PCV were completed
3. Design and drawings for the hydrogen compressor were completed.

The procurement and manufacture of the majority of BSE components took place during this period. During this process, the need for drawing changes arose from several causes. In some instances, the specific material or alloy called for on a drawing, or a specific thickness or shape of raw material, could not be obtained without inordinate cost or schedule delay. Machining vendors stated that they could not hold the tolerances called for in some cases. In other instances, partial machining of a complex part revealed inconsistencies of the drawing dimensions or configuration that were not apparent when the drawing was made. All of these occurrences result in a review of the drawing in question, formulation of a correction or revised design, and engineering change notices and revised drawings for the specific part and for adjacent or related parts affected by the primary change. During the period July 1 - December 31, 1985, a total of 89 engineering change notices were issued, affecting 162 Mod II engine drawings.

### PCV

The PCV is a multi-port spool valve which accomplishes the functions of gas supply and dump to and from the engine, and short-circuiting between P(max) and P(min) in the engine. The linear motion required by the valve spool is supplied by a rack-and-pinion actuator. The pinion is driven by an 8 V DC motor through a speed-reducing gearbox. The actuator/valve assembly is shown in Figure 5-1.

The valve itself consists of an external, pressure-containing body, the valve sleeve and the sliding spool assembly. The body is machined from 416 stainless hardened to Rc26-30 to provide the desired strength and fatigue life. One side-face of the body is machined to mate against the check-valve block on one side of the engine crankcase, to be held in place by the same four bolts that secure the check-valve block to the engine. The actuator assembly is mounted on one end-face of the valve and held in place by four studs threaded into the actuator body, passing axially through the valve body, with nuts on the opposite end. The valve body also houses a gas filter for the P(max) line to protect the controls from any wear debris that might be generated in the engine.

The sleeve is machined from 440 stainless steel, hardened and tempered to provide strength and a long-wearing internal surface. The  $\phi 12$  mm bore surface on which the spool seals ride is polished to a nominal 0.5  $\mu$  meter surface finish. The several separate flow chambers in the valve are separated by O-ring seals installed on the O.D. of the valve sleeve.

---

\*Figures can be found at the end of this section beginning on page 5-7.

The sliding spool is machined from Nitronic 60 steel, and carries five Shamban seal rings with Viton back-up O-rings. These seal rings, sliding over the radial holes drilled in the wall of the sleeve, perform the flow-metering function of the valve. The actuator assembly is built up on an actuator body of 6061 T-6 aluminum, which is clamped to the valve body by the four studs previously mentioned, with a separate seal-housing piece between these two parts. The actuator body houses an oilite bronze bushing in which the cylindrical actuator rack slides, co-linear to the valve spool. The actuator housing also provides a mounting flange for the speed-reducer gear box and drive pinion, which project at right angles to the axis of the rack and valve spool. The drive motor mounts on top of the gear box with an aluminum adaptor plate to accommodate the different mounting bolt circles of these two commercial units. The drive-pinion shaft extends from the gear box beyond the rack and is supported on the outboard end by a ball bearing whose outer race is secured in the actuator body.

Despite accurately toleranced pilot fits between the actuator body and the valve body, it was recognized that some misalignment might exist between the actuator rack and valve sleeve. If the attachment between the rack and valve spool were rigid, this misalignment could cause binding, accelerated wear, or malfunction of the valve/actuator assembly. A flexible link was provided between the rack and valve spool in an effort to accommodate this potential misalignment. This flexible link consists of a  $\phi 3$  mm rod 90 mm long connected to the actuator rack on one end and to the valve spool on the other end. The bending stiffness of this member is relatively low and can accommodate the slight misalignment which may occur between the rack and spool. Overall length of the assembly was conserved by drilling the valve spool to  $\phi 5$  mm, and extending the flexible rod through this hole to attach to the spool at the end opposite the actuator.

The rack and pinion are both made from Nitralloy 135 M, with a core hardness of  $R_C 35-40$ . After the gear teeth are cut, they are ion-nitrided to provide a case hardness of  $R_C 65-70$  at 0.1 mm depth. The gear teeth have a diametral pitch of 17/in., and  $20^\circ$  pressure angle.

Oil lubrication is provided for the rack/pinion mesh, the bushing which supports sliding motions of the cylindrical rack member, and for the ball bearing on the outboard end of the pinion shaft. An oil reservoir or sump is mounted on the end of the actuator body opposite the valve. Oil supply and return holes are drilled from this reservoir to each end of the rack-bushing cavity.

The actuator body also is machined to house an LVDT, which provides an electrical feed-back signal of valve position. The cylindrical stator body of the LVDT is housed and clamped to the actuator body, parallel to the rack/spool axis. A small, rigid link is fastened to the outboard end of the rack and to the sliding armature of the LVDT, so that rack motion is exactly reproduced by the LVDT armature.

#### Hydrogen Compressor

The hydrogen compressor for the Mod II is a single-stage, double-acting unit with three separate volumes or cylinders and three pistons all mounted coaxially on a single piston rod. The compressor is mounted on the engine front cover, which is an aluminum extension of the cast-iron engine block. The front cover houses the connecting rod for the compressor and also supports the water pump and its drive gear. The compressor connecting rod is driven by its own throw on the engine crankshaft. This throw provides a stroke of 20 mm. The big-end rod bearing is an SKF needle roller bearing, type KZK40x48x20, with a one-piece, non-split roller cage. At the top of the connecting rod, a  $\phi 20$  mm full-floating wrist pin is used. The wrist pin bearing in both connecting rod and crosshead is Glacier Metals Co. Deva metal, a sintered tin

bronze/graphite/lead formulation with a surface load capacity of 200 N/mm<sup>2</sup>.

The compressor design is such that loads on the wrist pin bearings reverse their direction within each stroke in the full bypass or round-pumping mode, and four of the five pumping modes. This load reversal creates squeeze-film lubrication of the wrist pin bearings, which will reduce wear and extend the life of the wrist pin bearings, compared to a design with nonreversing loads.

The full-floating wrist pin is retained laterally by metal "buttons" with spherical-shaped ends inserted into each end of the wrist pin. The spherical end has a radius of curvature slightly less than that of the crosshead guide bore, and these ends can ride lightly against the crosshead guide bore to center the wrist pin.

The displacement of the three different cylinders are 4.0, 12.0, and 12.6 cc. The compressor configuration is shown schematically in Figure 5-2. By use of external, solenoid-actuated bypass valves, the three different compressor volumes or cylinders can be used singly or in combination to provide any one of five different compressor displacements. This step-wise variable displacement is advantageous for rapid pump-down of engine pressure for power-reduction transients. An accelerated pump-down reduces the amount of short-circuiting (which wastes energy) and therefore increases mpg over a driving cycle involving several power-reduction transients. By use of two gas-storage bottles operating at two different pressures (10.7 and 20 MPa), the maximum operating pressure ratio required of the compressor is only 5:1, even when engine idle pressure is reduced to 2 MPa.

The compressor consists of five major subassemblies: the crosshead guide body, the main housing or body assembly, the body top piece, the piston/rod/crosshead assembly, and the rod seal assembly. A cross-section of the compressor assembly

is shown in Figure 5-3. The crosshead guide body consists of a carbon steel body with a gray cast-iron sleeve pressed into the bore. The two-piece construction allows the formation of an annular lube-oil manifold around the crosshead guide, with oil feed orifices drilled through the liner to inject oil into the squeeze-film clearance gap between the crosshead and guide. The manifold receives oil through a drilled passage that mates with a feed hole from the engine front cover. This passage also carries oil up to two radial jets that spray oil onto the piston rod just below the rod seal.

The rod-seal housing piece mounts on top of the crosshead guide body, and pilots in the crosshead guide bore. A pumping-ring seal configuration is used, since this has given longer service life than the PL type of seal during earlier development tests of a two-stage, prototype compressor for the Mod II engine. The seal-housing can readily accommodate retrofit of a PL type of seal if this is found to be desirable after initial trials.

The main compressor body also seats on the top of the crosshead guide body, piloting on the O.D. of the seal housing. The compressor body contains a cylinder bore common to both the 12.0 and 12.6 cc cylinders, a discharge port for each of these two cylinders, a single suction port common to all three working volumes, and a cooling-water jacket with water-inlet and outlet connections. The body is rough-machined from 17-4 PH stainless steel. The water jacket is formed from 17-4 PH sheet metal formed around the body and around the two discharge-port nozzles, and welded to form a water-tight shell. After welding, the entire weldment is precipitation-hardened (heat treated) to the H 1150 condition. This provides a 0.2% yield strength of 724 MPa, stress relieves the weldment, and provides improved resistance to stress corrosion cracking. After finish machining, the cylinder bore surface is ion-



nitrided to a hardness of Rc68 for good wear resistance.

The body top piece mounts on top of the main body and pilots in the cylinder bore of the main body. The top piece contains the cylinder bore for the topmost, 4.0 cc working volume, the discharge port for the 4.0 cc cylinder, and a cooling-water jacket with inlet and outlet connections. The interconnect between water jackets on the main body and top body is done with an external hose. The body top piece is also made of 17-4 PH, precipitation hardened to H 1150 condition after welding.

The body top piece also has four through-holes for mounting bolts. These bolts extend the full length of the compressor assembly external to the main housing and crosshead guide body, and thread into helicoils on the mounting face of the engine front cover.

The piston rod and crosshead are an integral unit machined from Nitralloy 135 M. The material is through-hardened to Rc38-40 after rough machining to develop the desired strength. After semi-finish machining, the crosshead O.D. surface and rod surface that engages the seal are nitride hardened to Rc68-70 and then finish ground and polished.

The larger piston serving the 12.0 and 12.6 cc working volumes is clamped to a shoulder on the top end of the piston rod. The smaller-diameter piston, serving the topmost 4.0 cc working volume, threads into a hole on the top of the larger piston.

The single suction port on the main housing feeds into a suction cavity located between the 12.0 and 12.6 cc working volumes and their discharge ports. The suction cavity is actually formed by an annulus machined on the larger piston. In addition, internal drilled passages in the larger and small pistons communicate from this suction cavity to the annular suction cavity under the piston ring of the 4.0 cc working volume. The piston rings on each of the three pistons con-

sist of one solid and one split ring, each made of Rulon. The piston rings, in conjunction with drilled ports in the piston faces on which the rings seat, behave as check valves in a manner similar to the reed valves of commercial reciprocating gas compressors. The rings allow gas to flow from the suction cavity into the working cylinder on the suction stroke, and seal tightly on the compression stroke. The working cylinders are sealed at the opposite end by cap seals around the piston rod, similar to those used on the power piston rods. Each of the three discharge ports has a check valve threaded into the port drilling. These are disk-and-spring type check valves identical to those used elsewhere in the Mod II engine control system.

## Mod II Analysis

Analysis efforts during this report period focused on the three following areas:

1. Documentation of codes conceived and used for Mod II design efforts
2. Analysis of partition wall losses from P-40R testing
3. Determination of fuel economy and acceleration rates for the Mod II baseline vehicle with the IC engine.

To support the Mod II design effort, several computer codes were formulated. These included:

Appendix Gap Loss (AGL) Code - Losses associated with the partition wall, particularly in an annular engine configuration, are not well understood. The AGL code was built to support analysis of these losses.

Hydrogen Compressor Code - A key factor in obtaining attractive fuel economy with the Mod II engine rests on the ability to decrease engine power level rapidly when required. This requires that the hydrogen compressor and storage system be

carefully designed to provide the desired down-powering characteristics. The hydrogen compressor code was formulated to support this effort.

Vehicle Simulation Refinement - Prior to Mod II, no effort had been made to account for down-powering effects on the fuel consumption. The VESIM code was revised to include these effects.

Preheater Code - This code was assembled to model the preheater in order to support the selection of preheater type (ceramic or metallic) and emission control approach (EGR or CGR).

EHS Code - Expanded from the preheater code to include other EHS components and the interaction of the heater head in performance of the EHS.

These codes are all being documented and will be released in the near future. During this report period, the AGL code documentation was completed. Details of the analysis were presented in SA8. The code was released in a report in December 1985 (85ASE487ER79)

P-40R testing was conducted to further understand partition wall losses. The P-40R is an annular version of the P-40 engine. Its configuration is shown in Figure 5-4. To evaluate losses, several different partition wall configurations were tested. Figure 5-4 illustrates the short partition wall configuration where only the upper partition wall portion was changed for the tests. Three upper walls were used: solid stainless, solid nickel, and hollow stainless in order to evaluate the change in losses with changes in partition wall conductivity. The same wall changes were made for a long partition wall, where the lower wall, as shown on Figure 5-4 is an integral part of the upper wall, and is changed then for each test. Long wall testing was conducted in 1984. Results of the testing showed that the hollow partition wall (lowest conductivity) deformed during tests, so that results were not meaningful. Tests of the remaining walls showed that the high-

est conductivity walls, the nickel walls, had the greater losses. However, there was considerable data scatter. It was deduced that better data resolution would be accomplished by limiting partition wall change to the regenerator wall only, resulting in the short wall testing.

In the short wall test series, the hollow wall also deformed and test results again were not meaningful. The short walls again showed the nickel walls to have the higher losses, although the differences were less than those measured with the long walls, as expected. Again, however, data scatter was considerable. Use of the Stirling analysis code to compute partition wall radial loss resulted in loss of 13 kW at full load for the stainless wall. Losses predicted for a similar configuration (Mod II) with the AGL code would have predicted losses of only 5.2 kW at full load. Investigating the P-40R for other potential loss sources, the fit between the partition wall and heater head and between the partition wall and cooler were found to be potential problem areas in internal gas leakage. The fit to the heater could permit as much as 17% bypass flow around the heater and the cooler fit as much as 5% directly to the cold space. To eliminate potential leakage effects, design modifications to increase overlap in the heater head insertion and to improve sealing to the cooler will be made and the tests repeated. Findings of these potential leakage paths indicate that Mod II final build configuration must also be carefully checked dimensionally to ensure leakage is minimized.

Celebrity baseline testing was conducted to establish IC performance levels. Driving cycle tests and accelerations were performed. Results are shown on Table 5-1. The EPA-certified fuel economy for these vehicles is also shown on the table. The test results indicated that the vehicles are in fact representative of the published fuel economy levels (within 3% combined cycle mileage). It is then concluded that the published EPA values can in fact be used as the IC

baseline levels. The acceleration figures, as tested, will be used for the IC baseline numbers as no EPA certification exists for accelerations.

TABLE 5-1  
IC-CELEBRITY

Manual Transmission per 1985 EPA  
Certification Shift Indicator  
Light Shift Schedule

Inertia weight: 3000 lb  
Dyno hp: 7.3

	Test Result (mpg)	EPA Cert. (mpg)	%
Urban	27.7	26.5	+4.5%
Highway	38.7	39.5	-2.0%
Combined	31.8	31.1	+2.3%

Accelerations		Requirement
0-60 mph	14.7 sec	15.0
50-70 mph	10.6 sec	10.5

Automatic Transmission per  
EPA 1985 Certification

Inertia weight: 3125 lb  
Dyno hp: 7.3

	Test Result Average (mpg)	EPA Cert. (mpg)	%
Urban	25.6	25.7	+0.4%
Highway	40.3	41.6	-3.1%
Combined	30.6	31.0	+1.3%

Accelerations		Requirement
0-60 mph	16.7 sec	15.0
50-70 mpg	11.2 sec	10.5

## Mod II Hardware Procurement

The Mod II engine procurement was completed to the extent that the engine assembly began on November 15, 1985. At this point, the analogue engine block was received in good condition and assembly could start. The original assembly start date was September 30, 1985. The late delivery of drawings delayed the actual assembly start-up. It is still expected that through the use of overtime to correct design problems in the MTI Model Shop and for assembly, the engine start date could be maintained as January 31, 1986.

Several design problems have been uncovered at this point none of which has been serious in the sense it could not be accommodated or repaired in house. Several compromises on the first build are likely. The cast heater head housings have improper wall thicknesses due to core shift and the first head will have to be limited to 10 MPa maximum pressure. These heads will, however, serve the purpose for functional testing.

The engine will be initially tested as a BSE, which means that all electrical, fuel, and air requirements are externally furnished. Characterization of the engine will be completed by June 30, 1986. The engine will then be assembled into a SES where the engine itself provides all auxiliary and control power.

ORIGINAL PAGE IS  
OF POOR QUALITY

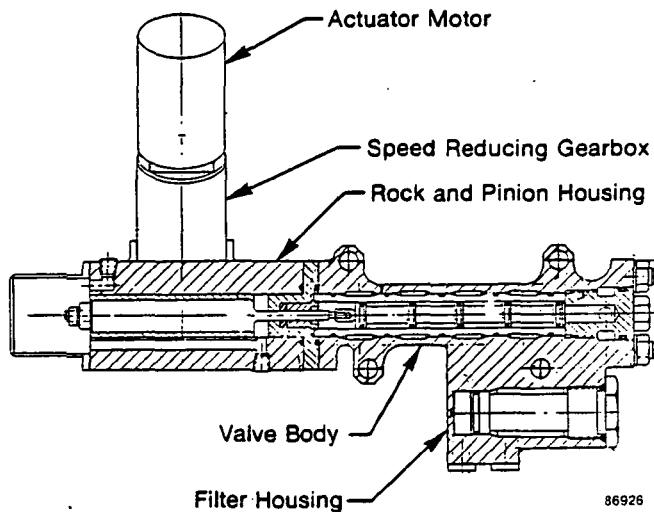


Fig. 5-1 Cross Section of Actuator

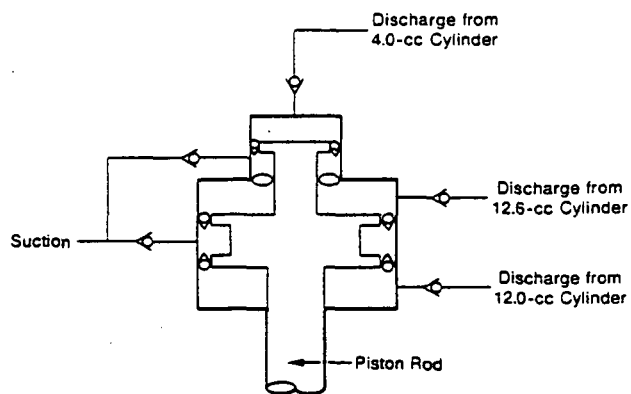


Fig. 5-2 Schematic Representation  
of Mod II Hydrogen Compressor

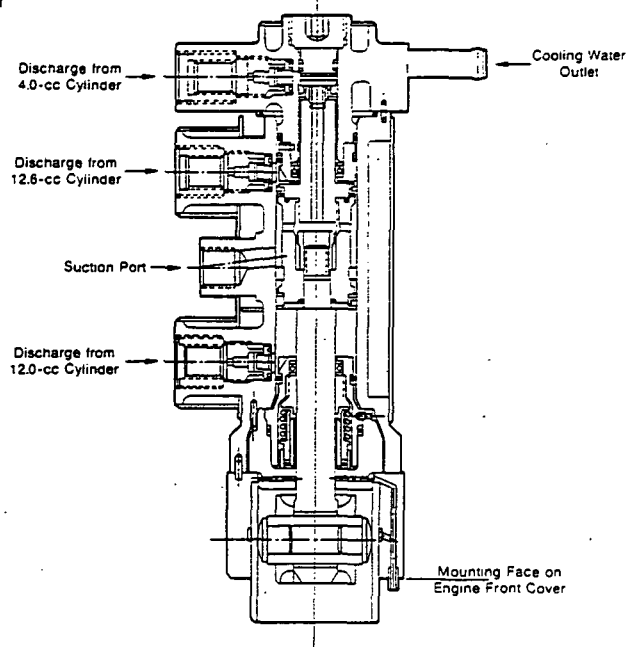


Fig. 5-3 Hydrogen Compressor Assembly  
for Mod II Engine

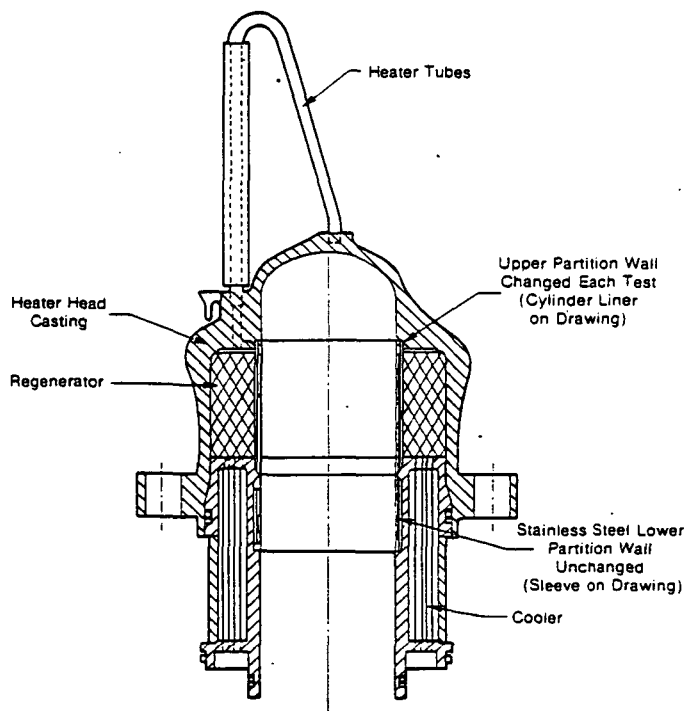


Fig. 5-4 P-40R Cylinder Cross Section

## VI. TECHNICAL ASSISTANCE

---

### Lateral Rod Motion

There is evidence that lateral or angular motion of the piston rod relative to the main seal can have a detrimental effect on the life of the seal. To investigate the sensitivity of seal life to nonlinear rod motion the exploratory rig will be modified to introduce this type of motion.

A design has been completed which will allow the test rod to be driven in a

lateral direction adjacent to the upper seal. The driving force will be applied through hydrostatic pads with the rod motion controlled by a hydraulic servo system. The system will also provide for control of the phasing between lateral and axial motion of the test rod.

Rig hardware is being procured and modification should be completed during the first half of 1986.

## VII. PRODUCT ASSURANCE

### Quality Assurance Overview

The status of the ASE Program Quality Assurance Reports (QARs) as of December 30, 1985 is presented below:

Open QARs (pending further analysis and/or NASA approval)	446
Closed QARs (total to date)	1344
P-40 QARs	269
Mod I QARs	617
Upgraded Mod I QARs	777
Preliminary Mod II QARs (Durability Rig)	59
Mod II QARs	44
Total QARs in system	1790

Program QAR activity for the second half of 1985 is as follows:

New QARs (for six-month period)	324
P-40 QARs	6
Mod I QARs	59
Upgraded Mod I QARs	198
Preliminary Mod II QARs (Durability Rig)	2
Mod II QARs	41

### Mod I QAR Experience

A summary of trend-setting problems documented via the QAR system is presented in Table 7-1 (shown on page 7-2), and Figures 7-1 through 7-4. Problems are defined as items that: 1) cause an engine

to stop running; 2) prevent an engine from being started; or, 3) cause degradation in engine performance. Problems that fall into these categories must be minimized to provide acceptable engine performance, and maximize the mean time between failures.

Major trend-setting problems identified for individual units/assemblies that were established prior to June 30, 1983 are shown in comparison with the results of this reporting period and that of the previous Semiannual report period.

Table 7-2 is a summary of the operating times versus failures for all active ASE program Mod I/Upgraded Mod I engines.

TABLE 7-2

### OPERATING TIMES VERSUS FAILURES AS OF DECEMBER 30, 1985

Engine No.	Operation Time (hr)	Mean Operating Time to Failure (hr)
3	2023	112
5	1531	153
6	2711	387
7	4480	1120
8	1099	550
9	338	48
10	106	106

TABLE 7-1 - MAJOR PROBLEMS SUMMARY

Established Prior to 6/30/83	% of Total	Reports From 6/30/83 to 12/31/83	% of Total	Reports From 1/1/84 to 6/30/84	% of Total	Reports From 6/31/84 to 12/31/84	% of Total	Reports from 1/1/85 to 6/30/85	% of Total	Reports from 6/30/85 to 12/30/85	% of Total
Moog Valve	76.0	1	4.0	1	4.0	1	4.0	1	4.0	2	8.0
Heater Head	43.3	3	10.0	3	10.0	5	16.7	6	20.0	-	--
Check Valves	36.4	3	13.6	2	9.1	4	18.2	3	13.6	2	9.1
Combustion Blower	41.3	6	20.7	6	20.7	3	10.3	1	3.5	1	3.5
Fuel Nozzle	23.6	6	11.0	13	23.6	5	9.1	5	9.1	13	23.6
Igniter	50.0	1	10.0	0	--	2	20.0	0	--	2	20.0
Preheater	25.0	7	25.0	1	3.5	7	25.0	1	3.5	5	18.0
Atomizing Air Comp./Servo-Oil Pump	50.0	1	8.3	2	16.7	1	8.3	2	16.7	--	--
Combustor	20.6	4	11.8	2	5.9	4	11.8	5	14.7	12	35.2
Flameshield	24.0	3	12.0	0	--	10	40.0	4	16.0	2	8.0
PL Seal Assy.	24.2	3	9.1	8	24.3	7	21.2	1	3.0	6	18.2
Crankcase/Bedplate	--	2	40.0	0	--	1	20.0	2	40.0	--	--
Piston Rod	--	3	30.0	4	40.0	1	10.0	1	10.0	1	10.0
Mod I hours accumulated prior to 6/30/83 - 2689 % of hours - 18.9											
Mod I hours accumulated from 6/30/83 to 12/31/83 - 1881 % of hours - 13.2											
Mod I hours accumulated from 12/31/83 to 6/30/84 - 1848 % of hours - 13.0											
Mod I hours accumulated from 6/30/84 to 12/30/84 - 2263 % of hours - 15.9											
Mod I hours accumulated from 12/30/84 to 6/30/85 - 2731 % of hours - 19.3											
Mod I hours accumulated from 6/30/85 to 12/30/85 - 2787 % of hours - 19.7											

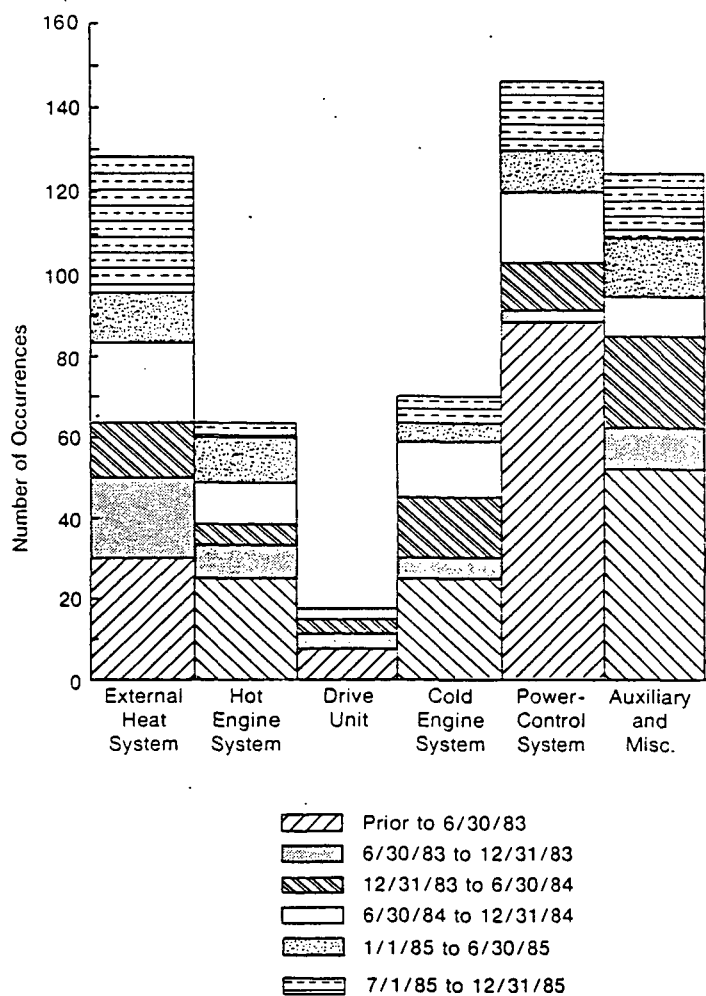


Figure 7-1 Upgraded Mod I Engine Major Failures and Discrepancies Through December 31, 1985

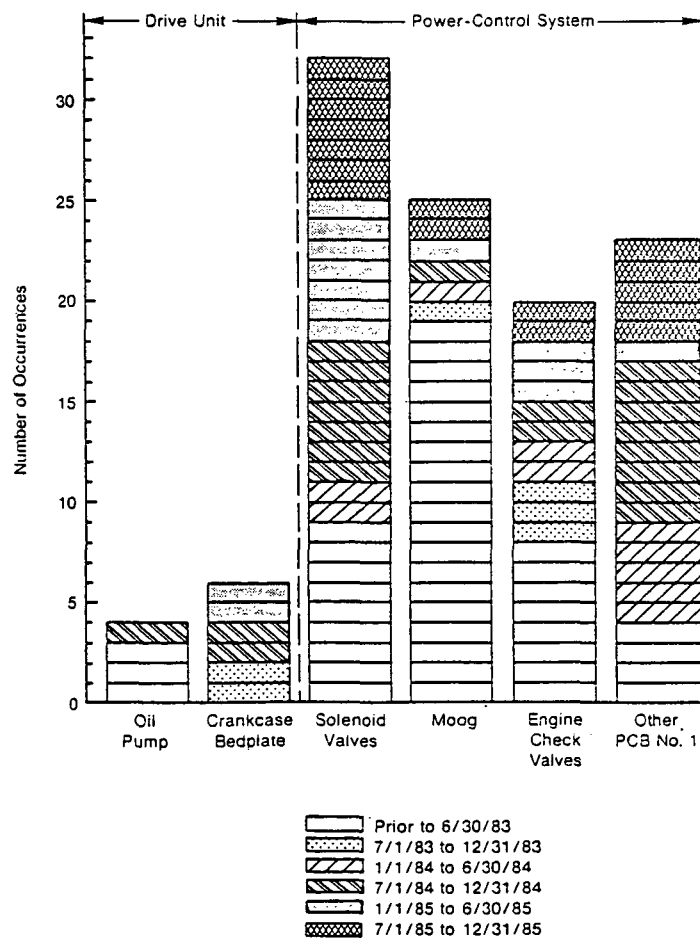


Figure 7-2 Drive Unit and Power-Control System Failures and Discrepancies Through December 31, 1985

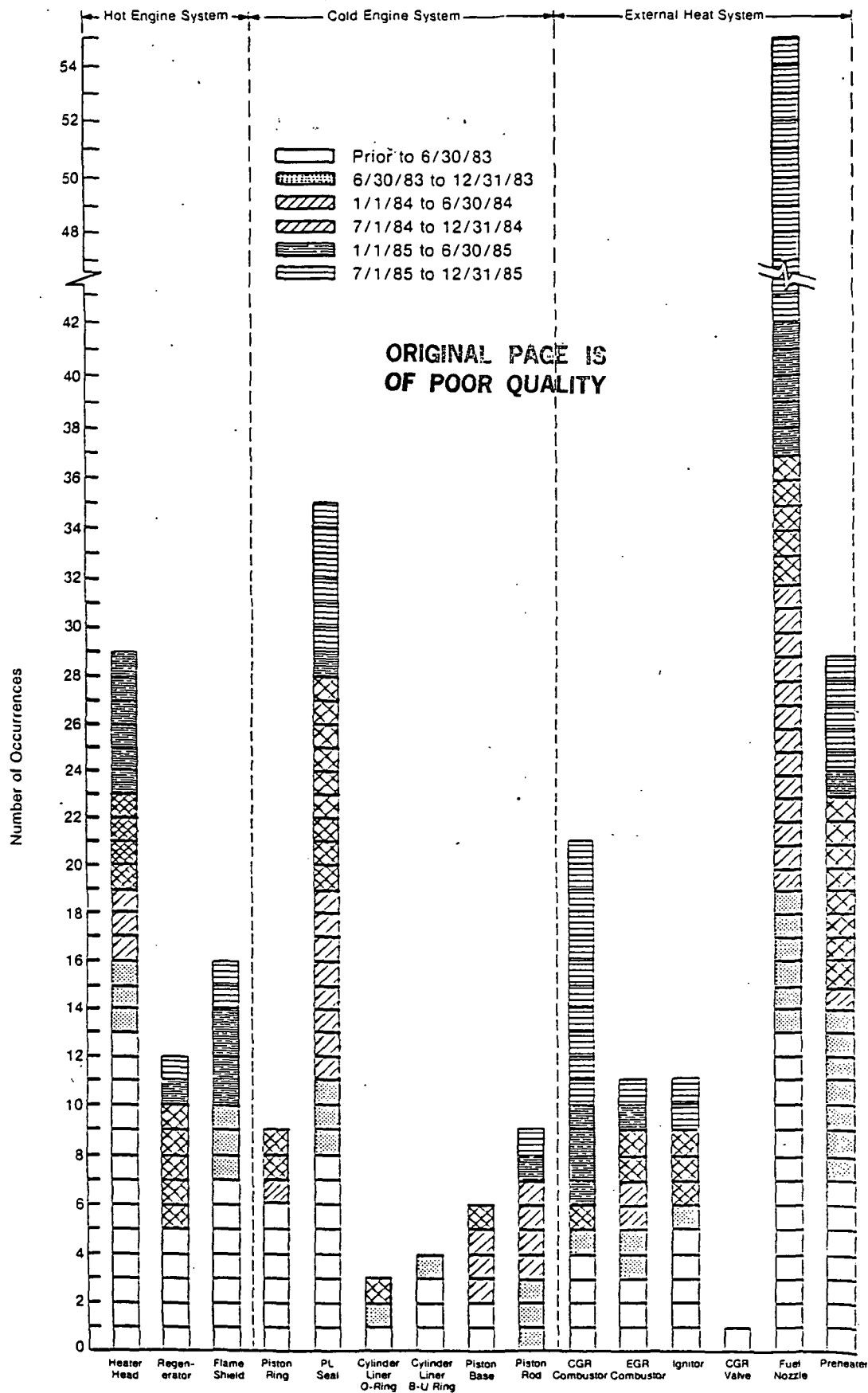


Figure 7-3 Hot Engine, Cold Engine, and EHS Failures and Discrepancies Through December 31, 1985

832753-4



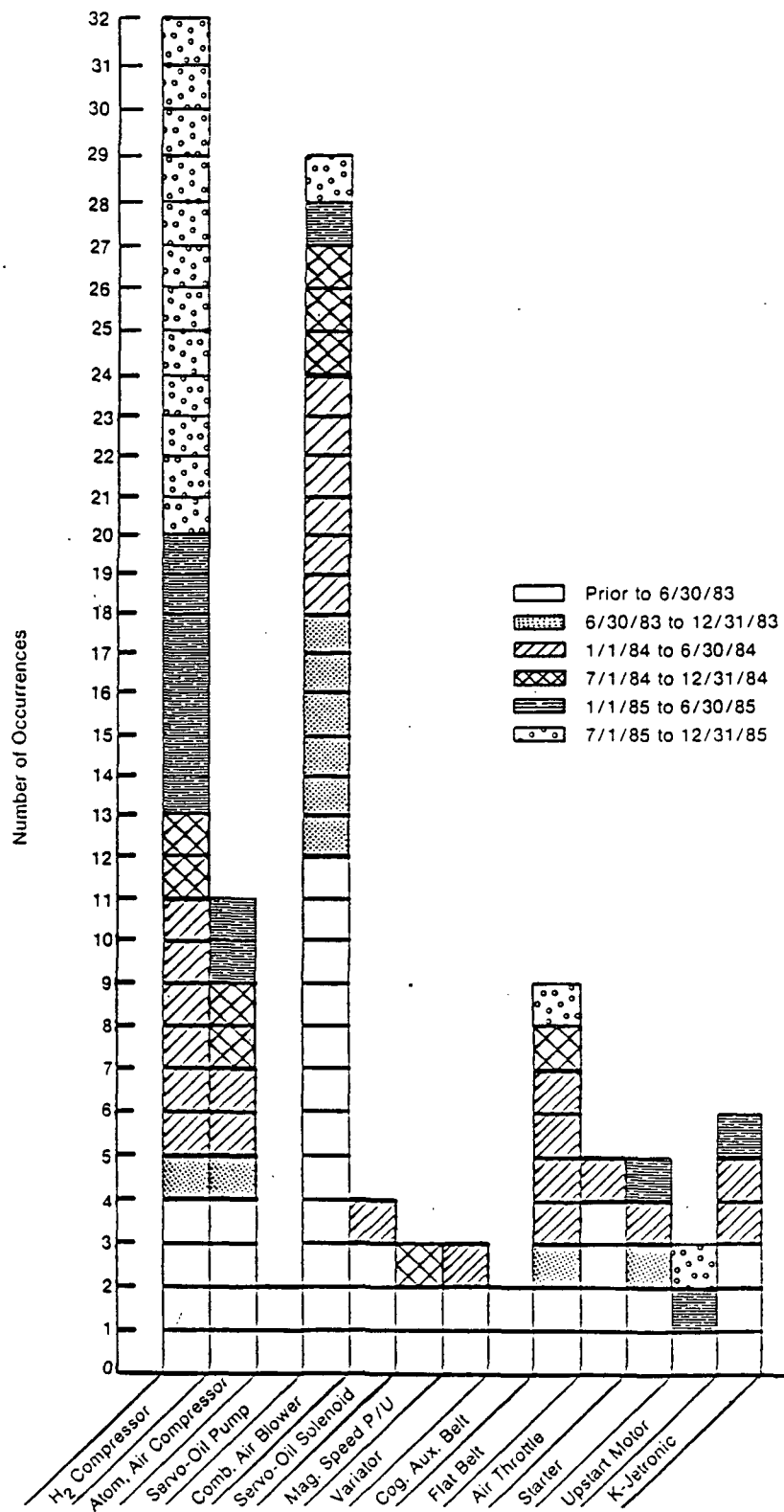


Figure 7-4 Auxiliaries and Miscellaneous Items, Failures and Discrepancies Through December 31, 1985

1. Report No. NASA CR-175045		2. Government Accession No. DOE/NASA/0032-27		3. Recipient's Catalog No.	
4. Title and Subtitle Automotive Stirling Engine Development Program Semiannual Technical Progress Report for Period July 1 - December 31, 1985				5. Report Date May 1986	
				6. Performing Organization Code	
7. Author(s) W. Ernst, A. Richey, R. Farrell, G. Riecke, G. Smith, R. Howarth, M. Cronin, M. Simetkosky, and J. Meacher				8. Performing Organization Report No. 86ASE507SA9	
				10. Work Unit No.	
9. Performing Organization Name and Address Stirling Engine Systems Division Mechanical Technology Incorporated 968 Albany-Shaker Road Latham, New York 12110				11. Contract or Grant No. DEN3-32	
				13. Type of Report and Period Covered Semiannual Technical July 1 - December 31, 1985	
12. Sponsoring Agency Name and Address U.S. Department of Energy Conservation and Renewable Office of Vehicle and Engine R&D - Washington, D.C.				14. Sponsoring Agency Code DOE/NASA/0032-80/7	
15. Supplementary Notes Semiannual Technical Progress Report prepared under Interagency Agreement DE-AI01-85CE50112, NASA Project Manager - William K. Tabata, Power Technology Division, NASA/Lewis Research Center, 21000 Brookpark Road, Cleveland, Ohio 44135					
16. Abstract  This is the ninth Semiannual Technical Progress Report prepared under the Automotive Stirling Engine Development Program. It covers the twenty-eighth and twenty-ninth quarters of activity after award of the contract. Quarterly Technical Progress Reports related program activities from the first through the thirteenth quarters; thereafter, reporting was changed to a Semiannual format.  This report summarizes the study of higher-power kinematic Stirling engines for transportation use, development testing of Mod I Stirling engines, and component development activities. Component development testing included successful conical fuel nozzle testing and functional checkout of Mod II controls and auxiliaries on Mod I engine test beds. Overall program philosophy is outlined and data and test results are presented.					
17. Key Words (Suggested by Author(s)) automotive Stirling engine, Mod I engine, Upgraded Mod I engine, seals, reference engine, airflow, fuel flow, Industry Test & Evaluation Program, Mod II engine, and heater head				18. Distribution Statement Unclassified - unlimited Star Category 85 DOE Category UC-96	
19. Security Classif. (of this report) Unclassified		20. Security Classif. (of this page) Unclassified		21. No. of Pages	
				22. Price*	

\* For sale by the National Technical Information Service, Springfield, Virginia 22151

MTI-17983